Chair of Petroleum and Geothermal Energy Recovery

Master Thesis

Thermal Insulation of Tubing in the Petroleum Industry

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Kurzfassung

Wärmeverluste sind ein Hauptproblem der Erdölindustrie. Besonders in der Erdölgewinnung kann das Abkühlen von produzierten Flüssigkeiten durch Paraffin- und Asphaltenabscheidung zu einer Verringerung der prouzierten Menge führen. Durch die thermische Isolierung des Steigrohres im Bohrloch kann ein Energieverlust und damit ein Abkühlen verhindert werden.

In dieser Arbeit wird eine Steigrohr-Isolierung aus verschiedenen Materialien analysiert, darunter Polyproylen-Schaum, Kalziumsilikat, Mineralwolle, Polyurethan-Schaum, Fiberglas und Aerogel. Zusätzlich wurde ein Einfluss durch das Anbringen auf der Innen- bzw. Außenseite der Steigrohre untersucht, sowie die Isolationsdicke betrachtet. Durch die Variation der drei Parameter Material, Anbringungsfläche und Schichtdicke konnte eine optimale Variante für die Isolierung von Steigrohren gefunden werden.

Zur Untersuchung der Varianten diente Schlumberger PIPESIM, eine Simulations-Software aus dem Erdölbereich. Dort wurde der Effekt der Isolierung auf die Produktionsrate, das Temperaturprofil und die Druckverluste im Steigrohr betrachtet. Zusätzlich wurde die Auswirkung auf unterschiedliche Öldichten (gemessen in API-Grad) simuliert. In Hinblick auf eine breite Anwendbarkeite wurden die Produktion von leichten (36° API), mittleren (26° API) und schweren Ölen (16° API) simuliert.

Die Resultate der Untersuchung zeigen, dass eine Steigrohr-Isolierung positive Effekte auf Temperatur- und Druckverluste im Bohrloch hat und damit auch die Produktionsrate verbessert werden kann. Als optimale Variante zeigte sich die Verwendung von einer Schicht aus Aerogel. Dabei schnitt die Beschichtung der Innenfläche des Steigrohres besser ab als jene der Außenflächen. Es konnte auch ein deutlicher Effekt der Schichtdicke auf die Isolationswirkung gezeigt werden. Die Arbeit zeigt schlussendlich, dass die Isolation von Steigrohren in der Erdölindustrie vor allem für die Produktion von schweren Ölen von Bedeutung ist, da hier die größte Verbesserung erzielt werden kann.

Abstract

Heat losses are a major problem in the petroleum industry. Especially in the upstream business, it can cause temperature reduction resulting in asphaltene and paraffin precipitation as well as loss in production. Insulating the tubing can be a solution to preserve the energy and to decrease the heat losses along the wellbore.

In this study, tubing insulation was evaluated using different materials, which are polypropylene foam, calcium silicate, mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel. The insulation was tested inside and outside the production tubing in order to select the best option. Moreover, the thickness of the insulation material was varied for both internal and external case to see its effect on the heat losses preservation and to pick its optimum value.

The different scenarios were simulated in PIPESIM Schlumberger software where the effect of insulation on the production rate, the temperature profile and the pressure losses of the well were studied. Furthermore, three different API gravities of oil were used in the simulation, which are light oil (36°API), medium oil (26°API) and heavy oil (16°API).

The obtained results have shown that using insulating materials helped on reducing the heat losses and pressure losses along the wellbore as well as increasing the production rate. The aerogel material has given the best results in comparison to the other insulation materials. In addition, internal insulation of tubing has produced better results than external insulation case. Furthermore, it was found that increasing the insulation thickness enhances the productivity of the well and decreases the temperature losses. The heavy oil scenario was the most influenced one by insulation in comparison to medium and light oil scenarios.

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List of insulation materials

AI	Aerogel insulation
CSPI	Calcium silicate pipe insulation
FG	Fiberglass
MPS	Micro porous silica insulation
MW	Mineral wool
NI	No insulation
PPF	Polypropylene foam
PUF	Polyurethane foam
TF	Thin-film insulation

List of symbols

g	Acceleration of gravity, m/s²
API	American petroleum institute
A	Area, inch²
z	Axial distance, m
r_{ci}	Casing inside radius, inch
r_{co}	Casing outside radius, inch
$Q_{cond,cyl}$	Conduction heat transfer rate of cylindrical layer, W
R_{cyl}	Conduction resistance of cylinder layer, K/W
R_{cyl}	Conduction resistance of cylindrical layer, K/W
R_{cond}	Conductive resistance, K/W
h_c	Convective heat transfer coefficient, W/m²K
R_{conv}	Convective resistance, K/W
ρ	Density, kg/m^3
D	Diameter, inch
I	Electrical current, ampere
R	Electrical resistance, ohm
H	Enthalpy, J/kg
R_f	Film resistance, K/W
T_f	Fluid temperature,°C
T_{ft}	Formation temperature, °C
C_p	Heat capacity at constant pressure, J/(kg.K)
$Q_{emit,max}$	Heat radiation emitted from a surface, W
Q'	Heat transfer per unit length, W/m
Q	Heat transfer, Watt
ID	Inside diameter, inch
r_{ins}	Insulation radius, inch
L	Length, meter
h_f	Liquid convective heat transfer coefficient, W/m²K
$\dot{m}$	Mass flowrate, kg/s
G	Mass velocity, kg.m/s
Max	Maximum
V_m	Mean velocity, m/s
Min	Minimum
Nu	Nusselt number
OD	Outside diameter, inch
U_{to}	Overall heat transfer coefficient, W/m²K
P	Pressure, psi
h_r	Radiative heat transfer coefficient, W/m²K
r	Radius, inch

R_{ann}	Resistance of the annulus, K/W
PIPESIM	Schlumberger simulation software
σ	Stefan Boltzmann coefficient, W.m.K $^{-4}$
A_s	Surface area, inch²
T_s	Surface temperature, °C
T_{ci}	Temperature at inner casing, °C
T_{ins}	Temperature at insulator, °C
T_∞	Temperature of the fluid sufficiently far from the surface
T	Temperature, °C
k_{cas}	Thermal conductivity of casing, W/mK
k_{cem}	Thermal conductivity of cement, W/mK
k_{ins}	Thermal conductivity of insulation, W/mK
k_{tbg}	Thermal conductivity of tubing, W/mK
k	Thermal conductivity, W/mK
α	Thermal diffusivity, m²/s
R_{cas}	Thermal resistance of casing, K/W
R_{cem}	Thermal resistance of cement, K/W
R_{ins}	Thermal resistance of insulation, K/W
R_{tbg}	Thermal resistance of tubing, K/W
R_{total}	Total thermal resistance, K/W
r_{ti}	Tubing inside radius, inch
r_{to}	Tubing outside radius, inch
V	Voltage, volt
WAT	Wax appearance temperature, °C
r_{wb}	Wellbore radius, inch

List of units

bbl/day	Barrels per day
C	Celsius
g	Gramm
“	Inch
J	Joules
K	Kelvin
kg	Kilogram
m	Meter
Pa	Pascal
s	Seconds
Scf	Standard cubic feet
STB	Stock tank barrel
W	Watt

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1 Introduction

Hydrocarbon production system in oil and gas industry faces many challenges such as heat losses along the wellbore and wax precipitation. The heat losses occur due to three heat transfer mechanisms: conduction, radiation, and convection. The wax and hydrate precipitation can plug the perforations, the tubing, and the flow line creating restrictions in the flow path, additional pressure drop and sub-optimal production conditions.

Hydrocarbon solids can precipitate within the wellbore and at surface facilities due to pressure and temperature decline during the production. Every type of precipitation has a specific pressure-temperature equilibrium. Therefore, most techniques for addressing solids deposition issues consist of avoiding the specific pressure-temperature equilibria that would promote precipitation. Thermal insulation is an alternative technique for retaining heat. It is commonly used in many industries such as aerospace, buildings, cryogenics as well as petroleum.

Thermal insulation system is an attractive solution for reducing the heat losses, improving the production rate of the well and preventing wax and hydrate deposition. In fact, it keeps the produced fluid at a temperature higher than the wax appearance temperature or the hydrate formation temperature throughout the length of the production conduit.

Thermal insulation consists of using low thermal conductivity materials such as polypropylene foam, polyurethane foam, calcium silica and aerogel. These materials are desirable for achieving maximum resistance to heat transfer. In fact, when applied to the tubing, they need to be:

- Tough
- Durable
- Corrosion resistant
- High temperature rating
- Withstand exposure to produced fluid, gases, and sour components.

Insulation materials can be installed either inside or outside the tubing depending on many factors such as tubular size and insulation thickness.

The overall heat transfer of the well has to be calculated to see the effect of insulation material on heat losses. It depends on insulation thermal conductivity, fluid convective heat transfer, annular radiative and convective heat transfer, well geometry, insulation thickness, the conductivity of tubing material, conductivity of casing material and conductivity of cement. An Excel model was created to estimate the overall heat transfer coefficient of the well for different scenarios.

This thesis aims to investigate the effect of thermal insulation of tubing on the heat losses, the well productivity and the pressure losses along the wellbore. Different insulation materials were evaluated, and their impact on the well performance was studied. The results were simulated by using Schlumberger PIPESIM software, which generates many output results such as the temperature profile, pressure losses and the production rate of the well. Insulation thickness is an important factor when selecting the insulation material. When installed inside the tubing, it could be limited due to tubing internal diameter size. A higher insulation thickness can be applied outside the tubing due to having more space in the annulus. The simulations were run with different thicknesses for both internal and external insulation of tubing and their effect on the production rate, and temperature profile was investigated.

The structure of the thesis starts with a literature review in which wellbore problems such as wax paraffin, and hydrates are explained. The different modes of heat transfer are presented, and the different types of thermal insulation material are introduced. Furthermore, the rock and fluid thermal properties are defined in the next chapter. Afterwards, the simulation study deals with the overall heat transfer model and the PIPESIM model. Three different oil API gravities were investigated in this part, which are light oil (36°API), medium oil (26°API) and heavy oil (16°API). The effect of insulation material on the overall heat transfer, production rate, pressure losses and temperature profile of the well were analyzed in this chapter. A comparison between different insulation materials and thicknesses was elaborated in this section as well. Then, a summary of the results and recommendations was presented. Finally, the last chapter compiles the main conclusions from the thesis.

2 Literature review

2.1 Wellbore problems, structure and construction

2.1.1 Wellbore problems

Due to recent developments in offshore, deep-sea and permafrost zones, field devolvement becomes complicated. Flow assurance is a critical issue in the design of petroleum fields in such new developed areas.

After drilling and completion of the well, the produced fluids are flowing through the tubing where flow assurance issues can occur. Actually, there are several problems for multiphase flow production in both onshore and offshore fields, which are summed up as follows:

- **Wax:** Waxes are high molecular weight, highly saturated organic substances. The main organic compound in crude oil that precipitates wax at production operating conditions are paraffin compounds, which are insoluble in the oil. Paraffin, consisting of carbon numbers greater than C_{20}, can cause problem for the production system. The prediction of the potential of wax deposition problems is fundamentally based on the determination of the physical characterization of the oil (paraffin content) and WAT (Wax Appearance Temperature). The formation of wax crystals depends mostly on temperature change, while pressure and composition also affect their formation but not to a significant extent. Large quantities of wax deposition can require a major shutdown operation to clear the blockage with associated economic penalties to the development and consequential loss in production and revenue.(White et al. 2017)

- **Asphaltenes:** Asphaltenes are defined, as high molecular weights, aromatic, polar compounds that are soluble in toluene but are precipitated by alkanes. Generally, asphaltenes tend to remain in solution or in colloidal suspension under reservoir temperature and pressure conditions. They may start to precipitate once the stability of the colloidal suspension changes, which is caused by alterations in temperature and/or pressure during primary depletion.(Yarranton 2000)

- **Hydrates**: Natural gas hydrates are ice-like solids that form when free water and natural gas combine with high pressure and low temperature. This can occur in gas/condensate wells as well as in oil wells causing the restriction of hydrocarbon flow or even plugging the pipeline entirely. Location and intensity of hydrate accumulations in a well vary and depend on (Carroll 2005):
    - Operating flow regime
    - Well design
    - Geothermal gradient of the system
    - Fluid composition
- **Slugging**: Slug flow in production pipelines, tubing and risers has been a major operational issue associated with subsea field developments. This creates problems associated with instability in production flow due to pressure fluctuations, which can be caused by any of the following (Tang and Danielson 2006).

Some of the stated problems can be reduced by using thermal insulation materials and coatings, which can be used to prevent the precipitation of waxes, paraffin, and protect against corrosion.

In general, the well structure allows us to identify how much space we have for the isolation. The typical wellbore structure is formed of surface and downhole equipment. Surface equipment includes the wellhead, christmas tree, chokes, gauges and tubing hanger. Downhole completion includes all the equipment, which are installed during the process of completing the well after the drilling process. The most important downhole completion equipment's are the casing string, the tubing string, the flow coupling and joints, the packers. The isolation space available for isolation depends primarily on the casing size and the tubing size.

The insulation of tubing can be either external or internal. In fact, isolating the tubing depends on the space available for insulation and on the type of material used. The isolation thickness selected should permit wash-over and fishing operations in order to allow access to the well in case of any tubing problem. In case of externally coating the tubing, the tubing OD and the insulation thickness must have adequate clearance with casing ID. The clearance differs from one well to another. Also, the tubing OD and the external coating thickness should permit the use of an overshot inside the casing, which limits the tubing OD size and/or the coupling OD.

Therefore, possible fishing operations should be taken into consideration to design successfully the thermal insulation coating.

To sum up, the tubing, casing and the temperature range of the well are the most important factors affecting the selection of the required space of the isolation.

The casing and tubing strings are explained briefly in the next section.

2.1.2 Casing

The general purpose of the casing is to support wellhead and subsequent casing strings, to provide a means of connecting the blowout preventers, to keep the hole open from collapse, to provide a means of controlling fluid inflow, to isolate producing horizons.

There are different types of casing strings:

- Conductor casing is installed to cover unconsolidated formations. The typical depth of this casing is between 10 and 30 meters. The standard size is between 16" and 30".
- Surface casing is installed to protect water aquifer sands and prevent loss of circulation. It is cemented to the surface or inside the conductor casing. This casing is the first string on which the blowout preventer can be set to provide pressure control. The typical size of surface casing is between 9 5/8" and 20".
- Intermediate casing(s): Normally cemented to the surface or in the previous casing shoe. The number of intermediate casings depends on well depth, hole problems and geological complexity (lost circulation, salt section, differential sticking, caving, over-

pressurized zones), fracture pressure at the last shoe, the proximity of the reservoir. The common size is between $9^{5/8}$" and $13^{3/8}$".

- Production casing is the string through which the well will be completed, produced and controlled through its life. It is installed to separate productive zones from other reservoir formations. It is usually cemented to the surface or the last casing shoe. The common size of the production casing is between 7" and 9 5/8". (IADC Drilling Manual 2015)

2.1.3 Tubing

The tubing is the pipe centered in the annulus of the well through which the oil, gas or water flows to the surface from the formation. Selecting the proper tubing size is necessary for the design of the well. Small tubing size will restrict the production and limit the profitability of the well. Nevertheless, large tubing size can reduce fluid velocity and allow for the build-up of produced water that can kill a gas well. It will also affect the economics of the project, adding to the cost of the overall well design.

Tubing connections play a vital part in the function of the tubing. There are two types available: API (external upset EU and non-upset NU) and premium connections.

The tubing size varies between 1.9" to 6", and it depends on design criteria of tubing size. The tubing roughness also differs from one material to another. The table below contains typical values of surface roughness for different tubing material.(IADC Drilling Manual 2015)

Table 1: Tubing materials and its roughness (IADC Drilling Manual 2015)

Material	Roughness (mm)
Stainless steel	0.03
Carbon Steel (new)	0.02 - 0.05
Cast Iron	0.25
Galvanized iron	0.25 - 0.15
Smooth cement	0.5
Drawn Tubing, Glass, Plastic	0.0015 - 0.01
Drawn Brass, Copper	>0.0015 - 0.01

2.2 The different modes of heat transfer

Heat is thermal energy. On a microscopic level, thermal energy is associated with the vibrations of atoms and molecules. Hence, it can be seen as a form of kinetic energy.

Temperature is indeed a measure of these vibrations. The heat transfer between two bodies at different temperatures is indeed an exchange of kinetic energy at a microscopic level. The high-temperature body passes energy to the low-temperature one, eventually achieving thermal equilibrium. The tendency to thermal balance, or even distribution of kinetic energy, is an expression of the second law of thermodynamics, the driving force of heat transfer. (Incropera 2007)

The matter is discrete, but for practical purposes, in human-scale objects, it is convenient to treat it as a continuum. An element is defined as a finite quantity of matter representable with a single value for a given property such as temperature. The size of the element is apparently dependent on the specific problem at hand.(Incropera 2007)

This section presents the underlying mechanisms of heat transfer, and it is the first cornerstone to simulate heat transfer phenomena. When working with a complex heat transfer problem, it is essential to identify the elementary relations. All three modes of energy transfer can only occur with the existence of a temperature difference.

In transient heat transfer, the temperature of an element is not constant over time. For example, solid parts can be exposed to varying thermal loads. Even at stationary thermal conditions, fluid elements in the flow move between areas at different temperatures. Its energy balance determines the temperature change in time of an element.

It depends on two different properties: on the one side, how the element conducts thermal energy, thermal conductivity k, and on the other, the amount of energy necessary to alter the element’s temperature, ρC_p (J/(m³·K)). Those properties can be grouped to define thermal diffusivity α (m²/s). (Siegel and Howell 1983)

2.2.1 Heat conduction

Heat conduction is the transfer of energy between neighboring molecules in a substance. The transfer occurs from the more energetic particles to the less energetic ones. Molecules increase in energy with an in an increase in temperature. Thus, the conduction occurs from molecules of high temperature to molecules of a lower temperature. Conduction is possible in solids, liquid, or gases. The rate at which conduction occurs is dependent on the geometry of the medium, thermal conductivity of the material, and the temperature gradient.(Çengel 2007)

$$\dot{Q}_{\mathrm{cond,cyl}} = -kA\frac{\Delta T}{\Delta r} \tag{1}$$

The thermal conductivity of the material is k, ΔT is the temperature differential, and $A=2\pi rL$ is the area. In the limiting case, $\Delta r \rightarrow 0$ the equation above reduces to the differential form that is called Fourier’s law of heat conduction after J. Fourier and becomes:

$$\dot{Q}_{\mathrm{cond,cyl}} = -kA\frac{dT}{dr} \tag{2}$$

After integration (Çengel 2007)

$$\int_{r1}^{r2} \frac{\dot{Q}_{cond,cyl}}{A} dr = -\int_{T1}^{T2} kdT \qquad A = 2\pi rL \tag{3}$$

$$\dot{Q}_{cond,cyl} = 2\pi kL \frac{T_1 - T_2}{\ln(\frac{r_2}{r_1})} = \frac{T_1 - T_2}{R_{cyl}} \tag{4}$$

R_{cyl} is the conduction resistance of the cylinder layer.

$$R_{cyl} = \frac{\ln(\frac{r_2}{r_1})}{2\pi kL} \tag{5}$$

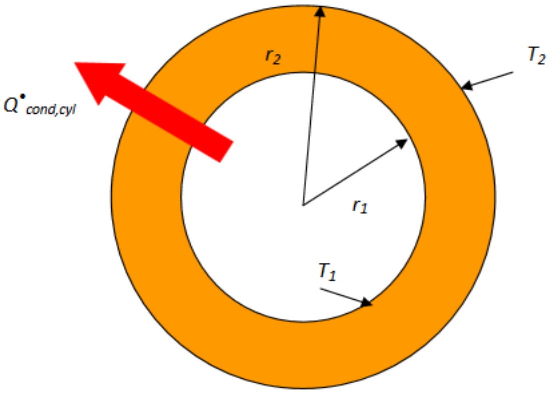


Figure 1: Heat conduction in a cylindrical layer (Çengel 2007)

2.2.2 Heat convection

Convection is the transfer of energy between a solid surface and an adjacent, moving liquid or gas. Convection occurs through the combination of conduction and fluid motion. The rate of convection increases at an increasing rate if the fluid motion is present. If the fluid motion is absent, conduction transfers the energy between the solid and fluid. Natural or free convection occurs when the fluid motion is caused by temperature differences, which results in density changes since density decreases with increasing temperature. Forced convection occurs when the fluid is artificially forced to flow over the surface by any external means such as a fan. (Incropera 2007)

A first attempt to deal mathematically with heat convection between a flow and its boundary is owed to Newton with his equation of cooling (Çengel 2007) :

$$\dot{Q}_{conv} = -hA_s(T_s - T_\infty) \tag{6}$$

The convective heat transfer coefficient is h (W/m².°C). A_s the surface area where convection occurs. T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far from the surface. The coefficient h cannot be determined by the nature of the fluid alone, but it is a property of the flow. It is, therefore, case-dependent and, in most cases, complicated to predict.

The Nusselt number (Nu) is a quantity derived using dimensional analysis (Çengel 2007). In symbols:

$$\mathrm{Nu} = \frac{\mathrm{hD}}{\mathrm{k}} \tag{7}$$

The coefficient h (W/m².°C) is one of the factors in the equation, making Nu a property of the flow as well. D (m) is a length of the geometry at the study, for the typical example of a pipe, D is the diameter. As a dimensionless quantity, Nu is of great help to transfer findings between similar cases. Nonetheless, the first step in understanding heat convection is the understanding of fluid flows. For most practical examples, this means dealing with turbulent flows.

2.2.3 Heat radiation

Radiation is the energy emitted by a matter in the form of electromagnetic waves, which can transfer heat without the presence of a medium. Specifically, thermal radiation causes the heat to be emitted from bodies that have a temperature above absolute zero. Thermal radiation is governed by reflectivity, absorptivity, and emissivity, which are dependent on the temperature. Radiation reflected off a surface is the reflectivity, which depends on the incoming direction, wavelengths and surface properties. The radiation source temperature determines the fraction of absorbed energy because it determines the distribution of the wavelengths. The net energy from radiation is the difference between the rate of emissivity by a surface and the radiation absorbed. A surface gains energy when the absorptivity is larger than the emissivity rate. Radiation co-occurs with either conduction or convection, which are dependent on the presence or absence of fluid. (Siegel and Howell 1983).

The Stefan-Boltzmann law gives the formula of radiation that is emitted from a surface at an absolute temperature. (Çengel 2007)

$$\dot{\mathrm{Q}}_{\mathrm{emit,max}} = \sigma \mathrm{A_s} \mathrm{T_s^4} \tag{8}$$

Where σ is the Stefan Boltzmann coefficient, A_s is the surface area, and T_s is the surface temperature (Çengel 2007).

2.2.4 Thermal resistance

An analogy comparing the conduction of heat with conduction of electricity is often used when studying heat transfer through multiple layers of matter (Incropera 2007). Ohms law gives the resistance of electrical conduction:

$$\mathrm{R} = \frac{\mathrm{V}}{\mathrm{I}} \tag{9}$$

Where R is the electrical resistance, V is the voltage, and I is the electrical current. When comparing to 1-D heat transfer, the heat flux, q, is the analogue to the electrical current, I. For the case of conduction, given by equation (4), the thermal resistance through a solid, R is given by (Incropera 2007) as:

$$R_{\mathrm{cond}} = \frac{\Delta T}{Q} = \frac{L}{kA} \tag{10}$$

Which gives:

$$Q_{\mathrm{cond}} = \frac{1}{R_{\mathrm{cond}}} \Delta T \tag{11}$$

Similarly, the convective heat transfer by a liquid can be written in terms of R: (Incropera 2007)

$$R_{\mathrm{conv}} = \frac{\Delta T}{Q} = \frac{1}{hA} \tag{12}$$

Which gives:

$$Q_{\mathrm{conv}} = \frac{1}{R_{\mathrm{conv}}} \Delta T \tag{13}$$

2.2.5 Overall heat transfer coefficient for cylindrical geometry

To make calculations more manageable when considering heat transfer through a system of several different layers, like a composite wall or cylindrical geometry, it is favorable to define an overall heat transfer coefficient, U analogous to Newton’s law of cooling, and defined by (Incropera 2007) :

$$Q = UA\Delta T \tag{14}$$

U (W/m^2K) is expressed as follow:

$$U = \frac{1}{R_{\mathrm{total}} A} \tag{15}$$

For cylindrical geometry, U is obtained in a similar fashion. Considering the radial heat flow across a pipe due to fluids of different temperature flowing along the axial direction of the pipe both inside and outside, the conductive heat transfer through the pipe can be expressed as:

$$Q = \frac{2\pi Lk\Delta T}{\ln(\frac{r_2}{r_1})} \tag{16}$$

Which gives the following expression for the conductive resistance, R_{cond} for radial geometry:

$$R_{cond} = \frac{\Delta T}{Q} = \frac{\ln(\frac{r_2}{r_1})}{2\pi r_1 Lk} \tag{17}$$

Similarly the convective resistance, R_{conv} for radial geometry:

$$R_{conv} = \frac{\Delta T}{Q} = \frac{1}{hA} = \frac{1}{2\pi rLk} \tag{18}$$

Where A is the surface the area at which the convection is considered, e.g. pipe inside or outside area.

The total radial heat transfer rate through the pipe can now be expressed as:

$$Q = \frac{\Delta T}{R_{total}} = \frac{T_{\infty,1} - T_{\infty,2}}{\frac{1}{2\pi r_1 Lh_1} + \frac{\ln(\frac{r_2}{r_1})}{2\pi Lk} + \frac{1}{2\pi r_2 Lh_2}} \tag{19}$$

Where $T_{\infty,1}$ and $T_{\infty,2}$ are the inside and outside average flow temperatures. The overall heat transfer coefficient U, in this case defined in terms of pipe inside area $A_1 = 2\pi r_1 L$, may be expressed as:

$$U_1 = \frac{1}{R_{total} A_1} = \left[\frac{1}{h_1} + \frac{r_1 \ln(\frac{r_2}{r_1})}{k} + \frac{r_1}{r_2}\frac{1}{h_2}\right]^{-1} \tag{20}$$

For each additional layer considered, a new resistance term is added in a similar fashion, and the respective overall heat transfer coefficient U is obtained. (Incropera 2007)

2.3 Thermal insulation

One of the significant flow assurance issues faced by the oil and gas industry is the formation of wax and paraffin in tubing and pipelines. In addressing hydrate and wax issues in petroleum production, it is essential to have a system, which can maintain the temperature of the hydrocarbon at an adequately high level to prevent the precipitation of wax and formation of hydrates and to enhance product flow properties.

Thus, a thermal management system is a method of controlling the temperature of the hydrocarbon that flows inside a tubing or flow line through heat containment and heat transfer. It has to be addressed at the beginning of the design stage of any producing well. So, thermal insulation can be used in the tubing to conserve energy. (Lively 2002)

Heat may be transferred through three mechanisms: convection, conduction, and radiation. Convection mechanism of heat occurs in liquids and gases. Free convection is flow caused by differences in density because of temperature differences. Forced convection is flow caused by external influences (wind, ventilators, etc.). Thermal conduction is the molecular transport of heat under the effect of a temperature gradient. Thermal radiation mechanism happens when thermal energy is emitted similar to light radiation. (Çengel 2007)

Heat transfers through insulation material occur by means of conduction, while heat loss to or heat gain from annulus occurs through convection and radiation.

Heat passes through solid materials through conduction, and the rate at which this occurs depends on the thermal conductivity (expressed in W/mK) of the material in question and the temperature drive. In general, the greater the density of a material is, the higher the thermal conductivity is. For example, metals have a high density and a high thermal conductivity. (Çengel 2007)

Materials having a high proportion of small voids containing air or gas must have a low thermal conductivity. These voids are not big enough to transmit heat by convection or radiation, and therefore reduce the flow of heat. If the density of insulation is low, the air or gas voids are relatively large and this makes for the best insulation for low to medium temperatures where compression and/or vibration are not a factor. (Karthikeyan 2015)

However, where higher temperatures are encountered, the air or gas voids inside the texture of insulation needs to be reduced in size to minimize the convection within the voids and this is achieved by increasing the density of the insulation. Density may be increased to a point where the solids content of the insulation is such that the heat bridge of the solids overcomes the insulating effect of the voids. It follows, therefore, that by encasing a container of heat with thermal insulation material the reverse heat flow will be retarded with resultant reducing energy loss and cost. (Karthikeyan 2015)

2.4 Tubing insulation materials

There are two types of insulation materials, which are the organic and inorganic type. Organic insulations are based on hydrocarbon polymers, which can be expanded to obtain high void structures. Examples include polypropylene and polyurethane foam (PUF). Inorganic insulation is based on siliceous/ aluminous/ calcium material in fibrous, granular, or powder forms. Examples include mineral wool, calcium silicate, etc. (Bahadori 2014)

2.4.1 Thin-film insulation

In harsh environments, the downhole insulation needs to be efficient in producing conditions. Therefore, it needs to have material properties not associated with traditional insulation coatings. It needs to be sturdy, durable and have a high-temperature rating, yet withstand exposure to produced fluids, gases and production chemicals. It needs properties similar to the performance properties of the internal coatings that have been used in tubing and drill pipe for many years. TF insulation is designed to meet those tough requirements.

TF insulation is a liquid epoxy coating that has been modified to provide resistance to heat flow. It may be used on either the ID or the OD of the pipe. (Lively 2002)

TF insulation adds less than 0.25” to the OD, enabling the design engineer to use larger production tubing without increasing casing size. Additional benefits realized by using internal coating is the protection against corrosion. The overall thermal resistance values are enhanced when both the ID and the OD are insulated.

The thin-film insulation coating may be combined with a woven fabric to minimize handling damage to the OD of coated pipe and to enhance thermal insulation values. Woven materials such as fiberglass will add strength and toughness to the coating system. This method enables standard handling equipment to be used during installation.

Some of the advantages of TF insulation over traditional downhole insulating products are much lower cost, versatility, smaller OD, excellent availability, and when used for the ID corrosion protection and flow efficiency are realized. TF insulation can be applied to couplings, valves, gauges, and other components in the completion string that are generally not insulated, thus addressing the historical problem of heat loss at these components. (Lively 2002)

2.4.2 Polyurethane thermal insulation

2.4.2.1 Polyurethane solid

It is a more mature advanced technology, for corrosion protection, good insulation performance, and long service life. Due to steel tube surface is very hard to get the outside air and water erosion, its service life is higher than the trench and overhead laying. Polyurethane insulation material, as a substitute for traditional insulation material, has good energy saving effect.

The structure of the heat insulation pipeline is divided into three parts: the steel pipe, the insulation layer, the anti-corrosion protection layer. The inner layer is welded steel pipe or seamless steel pipe, and the outer wall is brushed with anti-rust and anti-corrosion material or asphalt. The intermediate layer is a heat insulation layer, with low thermal conductivity, low moisture absorption, and high strength. The outer layer is a protective layer, which is made of glass fiber reinforced plastics with high strength, corrosion resistance and excellent waterproof. Composite polyurethane material is the recombination of special-property polyurethane with different types of hollow microspheres. With low density and high compression performance, it is mainly used in the field of high depth sea pipeline insulation.

According to Bahadori, the physical properties of polyurethane are as follow:

- Low thermal conductivity (0.155 – 0.17 W/mK): prevents heat loss with minimal insulation thickness

- Suitable for a wide temperature range: can operate between -160°C to +160°C

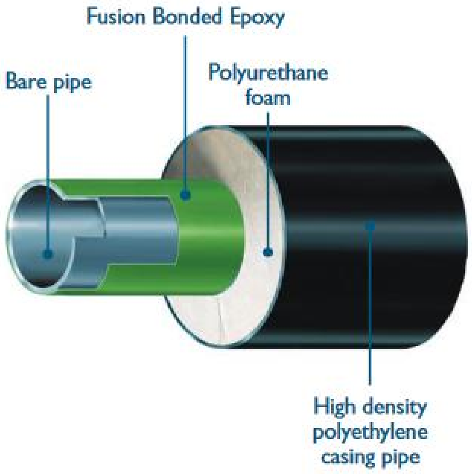


Figure 2: Polyurethane insulation coating

2.4.2.2 Polyurethane foam

Polyurethane foam is a material with excellent insulating properties. It is used in building and aerospace industry and in particular in pre insulated pipelines for district heating hot water distribution. The polyurethane foam is produced by mixing polyol and isocyanate together with a foaming agent. Nowadays, cyclo-pentane is used as the foaming agent because it has no impact on the ozone layer. Contrary to freons, which were used years ago. However, cyclo-pentane has the same stability and insulating properties as the earlier used freons.(S.PALLE 1998)

2.4.3 Polypropylene thermal insulation

Polypropylene materials used in the insulation of the submarine pipeline can be divided into three types:

- solid
- composite
- foamed

Solid polypropylene thermal insulation material is mainly composed of polypropylene composite material, without any physical strengthening and modification.

Composite polypropylene is made with hollow glass beads mixed in solid polypropylene composite. Composite multilayer polypropylene has good mechanical properties, low water permeability, and aging-resistant performance. The thickness and the number of layers are adjusted according to the need, and copolymer adhesive is adapted to improve the bonding between the layers. The structure has the characteristics of heat preservation, lightweight, compression resistance, non-penetration, stability, good toughness and environment protection, and can be repaired (Hansen and Rydin 2002). In general, the insulation system of multilayers polypropylene is composed of five layers, which are:

- Layer 1: Epoxy layer
- Layer 2: Polypropylene adhesive layer
- Layer 3: Solid polypropylene layer
- Layer 4: Syntactic polypropylene layer
- Layer 5: Solid polypropylene outer layer

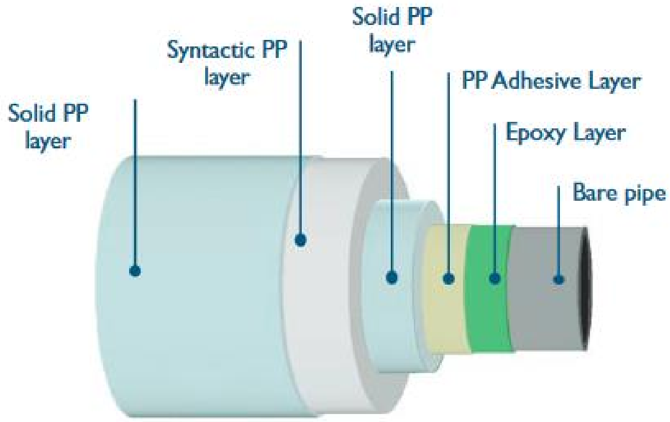


Figure 3: Multilayer polypropylene insulation (Hansen and Rydin 2002)

Polypropylene foam is a component of polypropylene filled with a large number of bubbles by physical or chemical methods. It has a high melt strength, elongation and a high stiffness. The properties of novel propylene foam are:

- Low water absorption 0.02-0.03%
- Easy and stable processing
- Density: 650kg/m³
- Tensile stress @yield: 13 MPa
- Tensile strain @break: 26 %
- Young's modulus: 830 MPa
- Compression modulus: 470 MPa
- Thermal conductivity: 0.169 W/mK; it differs from one company to another.
- Polypropylene foam operates in a temperature range between 0°C and 140°C.
- The type of coating and thickness to be used varies according to thermal insulation requirements. (Hansen and Rydin 2002)

2.4.4 Cellular glass/foam glass thermal insulation

Foam glass thermal insulation is a lightweight rigid insulating material composed of millions of completely sealed glass cells, each an insulation space. This all-glass, closed-cell structure provides an unmatched combination of physical properties ideal for piping and equipment aboveground, as well as underground, indoors, or outdoors. Service temperature range is -260°C to 200°C and 650°C in composite systems (Bahadori 2014). The properties of cellular/ foam glass insulation product are:

- Noncorrosive
- Resistant to water in both liquid and vapor form
- Resistant to many chemicals
- Non-combustible/non-absorbent of combustible liquids
- Superior compressive strength
- Constant, long-term energy efficiency provides low, predictable energy costs
- Minimal maintenance/ repair/replacement of insulation reduce life-cycle costs.

The physical properties of cellular glass insulation shall be as follow:

- The density of insulation varies depending on the other physical properties and can be between 112 to 152 kg/m³.
- The thermal conductivity of cellular glass thermal insulation is between 0.038 to 0.045 W/mK.
- Compressive strength shall not be less than 490 kPa according to ASTM test method C165.
- Water vapor transmission shall be zero according to ATSM test method (Bahadori 2014)

2.4.5 Mineral wool

Rock (stone) mineral wool is a furnace product of molten rock at a temperature of about 1600 °C, through which a stream of air or steam is blown. The final product is a mass of fine, intertwined fibers with a typical diameter of 2 to 6 micrometers. It is a non-combustible insulation and is produced from spun slag. (Bahadori 2014)

The properties of rock mineral wool insulation are:

- Flexibility
- Excellent thermal resistance
- Densities range from 60 kg/m³ to 160 kg/m³.
- The thermal conductivity is between 0.032 W/mK and 0.044 W/mK.
- Operating temperature up to 650°C

The major chemical components of mineral wool are SiO_2 (30–45 weight %), Al_2O_3 (8–15 weight %), TiO_2 (2–4 weight %), Fe_2O_3 (2.5 max. weight %), CaO (30–35 weight %), MgO (6–12 weight %), Na_2O (0–1 weight %), K_2O (0–1 weight %) and P_2O_5 (0–1 weight %). (Bahadori 2014)

2.4.6 Syntactic foam thermal insulation

Syntactic foam is manufactured by mixing polymeric resins with hollow glass microsphere. Polyurethane and epoxy resin system are dominant based on installed volume. This product has high compressive strength, low density, and thermal conductivity. In general, syntactic foam is usually used for insulating subsea equipment due to its thermal efficiency and water resistance (Watkins. Hershey 2001). The properties of syntactic foam used for insulation in offshore systems are shown in the Table 2.

Table 2: Ultra-deep water syntactic foam insulation materials (Watkins. Hershey 2001)

Syntactic construction type	Maximum Temperature °C	Thermal Conductivity W/mK	Specific heat capacity J/g °C
Rigid	80 to 100	0,08 to 0,12	1,28
Semi-Rigid	80 to 100	0,09 to 0,13	1,28
Flexible	80 to 100	0,1 to 0,15	1,28

The characteristic ingredient of syntactic foam is the tiny microsphere filler that imparts much of its thermal and physical behavior. Glass micro- spheres, typically 100-200 µm in diameter, retain much of their strength at elevated temperature. Certain types of ceramic microspheres also have excellent resistance to hot water, but their densities and thermal conductivities are not acceptable for many applications. (Watkins. Hershey 2001)

The advantages of using syntactic foam are:

- Low density. In most cases, syntactic foam provides the lowest density solution to any buoyancy or insulation requirement, at any depth.
- Low thermal conductivity. Again, in most cases, syntactic foam offers the lowest thermal conductivity at any depth, as compared to alternative materials.
- Virtually zero creep. Unlike other insulation materials, especially those based on thermoplastic foam, syntactic foam is inherently stable and does not creep under pressure.
- Integral buoyancy. The low density of syntactic foam permits a large amount of buoyant lift to be designed into the insulation system, if desired.
- Ruggedness and durability. Its great compressive strength makes syntactic foam resistant to crushing and mechanical damage during storage, handling, and laying.
- Adaptability. Because syntactic foam can be manufactured by several methods and in many forms, it can be adapted to any insulation requirement.
- Cost effectiveness. In many cases, syntactic foam has proven to be the lowest cost solution to insulating flow line and subsea equipment, often saving users hundreds of thousands of dollars per project. (Watkins. Hershey 2001)

2.4.7 Calcium silicate pipe insulation

Calcium silicate is a rigid, high-density material used for high-temperature application. It is composed principally of hydrous calcium silicate, and which usually contains reinforcing fibers. It is a lightweight, low thermal conductivity, and a high chemical resistance material. It is usually used in industrial areas such as the petrochemical and power-generating industries where energy conservation, process control, and fire protection are perquisites. (Bahadori 2014)

Calcium silicate thermal insulation is composed predominately of reacted hydrous calcium silicate and usually incorporates a fibrous reinforcement. The properties of this material are:

- Calcium silicate has high compressive strength – minimum 100 psi.
- The thermal conductivity: between 0.07 W/mK and 0.1 W/mK.
- Low density: 200 to 500 kg/m³
- The flexural strength of calcium silicate is higher than 250 kN/m^2.
- Compressive strength: shall not exceed 5% under a compressive load of 500 kN/m²
- Excellent thermal shock resistance
- Non-corroding
- Insoluble in water
- Resistant to weak alkalis, oils and many other chemicals (Bahadori 2014)

2.4.8 Aerogel thermal insulation

Aerogels are solids with high porosity (<100 nm) and hence possess extremely low density (~0.003 g/cm^3) and very low conductivity (~0.01 W/mK). In recent years, aerogels have attracted more and more attention due to their surprising properties and their existing and potential applications in wide range of technological areas.

Aerogel is a kind of gel material whose dispersion medium is gas. It is nano-porous solid materials with network structure made from colloidal particles or polymer molecular, and the size of the pores in the material in nano-meter scale. Pipe insulation made from Nano-aerogel have outstanding performance. It has super heat preservation, under the condition of high temperature or low temperature. The thermal conductivity of aerogels ranges between 0.011 W/mK and 0.014 W/mK, which is considered very low compared to the other types of coatings.

Aerogels have super temperature resistance. The temperature range is between 80°C and 650 ℃. Aerogel has super fire resistance, a high-temperature flame. It has not any toxic gas and smoke emissions, ultra-thin and ultra-light performance, easy to cut and easy to fold. Due to aerogels low thermal conductivity, it could prove to be highly efficient insulation that maintains a long thermal performance. (Thapliyal and Singh 2014)

2.5 Handling and fishing

2.5.1 Handling

Any coated tubing shall be handled in a manner to prevent damage to pipe walls, beveled ends, and coating during transportation and installation. The pipe, which is damaged by handling operations, shall be repaired in compliance with applicable pipe specifications.

The pipe should be handled with approved equipment employing wide canvas or rubber-covered slings and wide pads skids designed to prevent damage to the exterior coating. Bare cables, chains, hooks, metal bars, or narrow skids should not be allowed to encounter either the outer coating or the interior lining and should be used only with caution.

In fact, lifting slings used in direct contact with line pipe must be wide non-abrasive belts or padded cable loops. Forklifts utilized to move the tubing shall be properly padded. The end hooks shall be designed to avoid end damage and should be lined with soft metal, rubber or plastic when hooks are used for lifting line pipe. (DeGeare 2015)

To sum up, when handling coated pipes, we have to take into consideration the following rules:

- Planning storage, lifting, and transport in advance
- Coated tubes must not be lifted with chains or cables
- Making sure there is sufficient and correct auxiliary equipment
- Carrying out an acceptance inspection
- Protecting the pipe ends from damage

2.5.2 Fishing

Fishing should be well planned when adding internal or external insulation to the tubing. Well interventions like wireline and coiled tubing have to be performed at slow, controlled speeds to minimize their abrasive forces and reduce potential damage to the internal coating. Even when the fishing is appropriately implemented, the threat of damage is still a cause for concern when using internally coated tubing. (DeGeare 2015)

The ability of a coating to withstand damage is a function of its impact, abrasion and ductile properties. Operating tools in the wellbore are typically cylindrical bodies or bodies compromised of contagious cylinders of the varying radius that are conducted in the tubing, casing and open hole either on wireline or rigid pipe. As the wellbore inclination increases, the fishing tool can affect the internal coating of the tubing. Thus, the thickness of the coating that can be in contact with devices should be high enough to withstand the operation and avoid the damage. (DeGeare 2015)

When adding insulation inside the tubing, the internal diameter of the completion equipment should be adequate to allow passage of the fishing tools. Operational modes and tubing landing conditions can cause helical buckling of the tubing string, which also may interfere with running long lengths of devices through the tubing string.

2.6 Materials recommended

The insulation materials selected for the simulation part are as follow:

- Polypropylene Foam (PPF)
- Calcium Silicate Pipe Insulation (CSPI)
- Mineral wool (MW)
- Polyurethane Foam (PUF)
- Fiberglass (FG)

- Micro-porous Silica (MPS)
- Aerogel insulation (AI)

Table 3 shows a summary of the properties of insulation material.

Table 3: Insulation materials selected

Material		Insulation type	Thermal cond. W/mK	Operating temp. °C	Density kg/m³	Comp. strength MPa	Flex. Strength MPa
Polypropylene Foam	**PPF**	Foam	0.17	0 - 130~170	650	15~20	12~16
Calcium Silicate Pipe Insulation	**CSPI**	Silica	0.096	-18°C to 650	200 - 500	13	10
Mineral wool	**MW**	Rock fiber	0.04	0°C to 650	60 - 160	0.4	0.25
Polyurethane Foam	**PUF**	Foam	0.03	-160 to 160	30 - 100	0.64	0.2
Fiberglass	**FG**	Fine glass fibers	0.028	-30 to 540	10 - 14	0.1	n.a
Micro-porous Silica	**MPS**	Micro-porous-ceramic	0.02	0 - 600	260	1	n.a.
Aerogel insulation	**AI**	Nano size silica	0.012	up to 650	200	20	3

3 Model for overall heat transfer calculation

In this chapter, the overall heat transfer of the well is calculated for three different scenarios: no insulation, external and internal insulation of tubing.

3.1 No insulation model

Modeling heat transport in any system requires an energy balance for the wellbore fluid. Usually, the fluid element receives heat through fluid convection and loses heat to the surroundings through conduction. Heat loss (or gain) to the surroundings by the wellbore fluid depends on the formation temperature distribution in the presence of a heat source/sink like the wellbore, the temperature differences, and the resistance to heat transfer within the elements of the wellbore.

A basic well model is assumed firstly to calculate the overall heat transfer in the absence of insulation. Six zones were considered from the center of the wellbore to formation as shown in Figure 4.

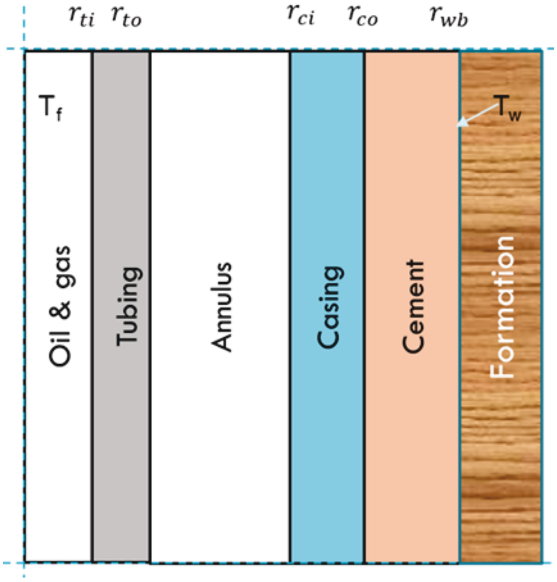


Figure 4: Structure of heat transfer model for wellbore without insulation

The pipe flow zone: where the fluid is flowing inside tubing

- The tubing zone
- The annulus zone: the spacing between the production casing and the tubing
- The casing material zone
- The cement zone: between casing and formation. As the cement usually has different thermal properties with the formation and pipe strings, it is necessary to define this zone separately.
- The formation zone: It consists of porous rock and fluids

The zones listed above are under different heat transfer processes. The pipe flow zone, with liquid flowing along the tubing, transfers heat with contacting tubing through convection. Convection also appears between the annular zone, and the contacting tubing and casing and radiation is also expected in this zone. On the other hand, conduction dominates the heat transfer inside tubing, casing, cement, and formation.

The momentum and energy equations for the steady state, one-dimensional flow in the tubing are given by: (Brill and Mukherjee 1999); (Hasan et al. 2002)

$$\frac{dP}{dz} = -(\frac{dP}{dz})_f - (\frac{dP}{dz})_g - (\frac{dP}{dz})_{acc} \tag{21}$$

$$\frac{dH}{dz} = -\frac{Q'}{\dot{m}} - g - v_m \frac{dv_m}{dz} \tag{22}$$

Where: P is the pressure, z is the axial distance, and the subscripts f, g ,and acc define the frictional, gravitational and acceleration pressure drop, respectively. In addition, g is the acceleration of gravity, H is the enthalpy in J/kg and Q' is the heat transfer per unit length in W/m, $\dot{m}$ is the mass flow rate in kg/s and v_m is the mean velocity in m/s. (Hasan et al. 2002)

$$Q = -2\pi r_{to} U_{to} (T_f - T_w) \Delta L \tag{23}$$

Where T_f and T_{ft} are the fluid and formation temperatures, respectively, U_T is the overall heat transfer given by: (Hasan et al. 2002)

$$\frac{1}{U_{to}} = \frac{r_{to}}{r_{ti} h_f} + \frac{r_{to} \ln(\frac{r_{to}}{r_{ti}})}{k_{tbg}} + \frac{1}{h_c + h_r} + \frac{r_{to} \ln(\frac{r_{co}}{r_{ci}})}{k_{cas}} + \frac{r_{to} \ln(\frac{r_{wb}}{r_{co}})}{k_{cem}} \tag{24}$$

Where r_{to} is the outside tubing radius, r_{ti} is the inside tubing radius, r_{co} is the outside casing radius, r_{ci} is the inside casing radius and r_{wb} is the wellbore radius. The parameters h_f, h_c and h_r represent respectively the liquid convective heat transfer coefficient, the convective heat transfer coefficient and the radiative heat transfer coefficient. The variables k_{tbg}, k_{cas} and k_{cem} are the thermal conductivities of the tubing, the casing and the wellbore.

Equation 24 was implemented on Excel model in order to calculate the overall heat transfer of the wellbore without insulation.

3.2 External insulation model

The model is built for external insulation of tubing. Since the insulator outer radius is in contact with the completion fluid, using the surface area and the temperature difference between the inner casing and the insulator, the heat transfer rate in the annulus can be given as: (Hasan et al. 2002)

$$Q = 2\pi r_{ins} (h_c + h_r)(T_{ins} - T_{ci}) \Delta L \tag{25}$$

Radial heat transfer occurs from the heat flow in the tubing to the formation, overcoming the resistance offered by the tubing wall, the tubing insulation, the insulation-casing annulus, the casing wall, and cement. The resistances are in series and pure thermal conduction, except for the resistance of the annulus and heat flow near the inner tubing. In steady state, the rate of heat flow through a wellbore, Q, can be expressed as:

$$Q = -2\pi r_{to} U_{to} (T_f - T_w). \Delta L \tag{26}$$

Where, U is the overall heat transfer coefficient in the wellbore (W/m²K), $(T_f - T_w)$ is the temperature difference between wellbore/formation interface and the wellbore fluid and, $2\pi r_{to}$ is the tubing outside area (m²). The overall heat transfer coefficient in equation 26 is mathematically described as the inverse of the thermal resistance.

$$U_{to} = \left((R_f + R_{tbg} + R_{ins} + R_{ann} + R_{cas} + R_{cem}) * 2\pi r_{to} * \Delta L\right)^{-1} \tag{27}$$

1. The film resistance of heat flow near the inner tubing is:

$$R_f = \frac{1}{2\pi h_f r_{ti} \Delta L} \tag{28}$$

2. The conduction resistance of the tubing is:

$$R_{tbg} = \frac{\ln(\frac{r_{to}}{r_{ti}})}{2\pi k_{tbg} \Delta L} \tag{29}$$

3. The conduction resistance of outside tubing insulation is:

$$R_{ins} = \frac{\ln(\frac{r_{ins}}{r_{to}})}{2\pi k_{ins} \Delta L} \tag{30}$$

4. The conduction resistance of the casing is:

$$R_{cas} = \frac{\ln(\frac{r_{co}}{r_{ci}})}{2\pi k_{cas} \Delta L} \tag{31}$$

5. The conduction resistance of the annulus:

$$R_{ann} = \frac{1}{2\pi r_{ins}(h_c + h_r) \Delta L} \tag{32}$$

6. The conduction resistance of the cement:

$$R_{cem} = \frac{\ln(\frac{r_{wb}}{r_{co}})}{2\pi k_{cem} \Delta L} \tag{33}$$

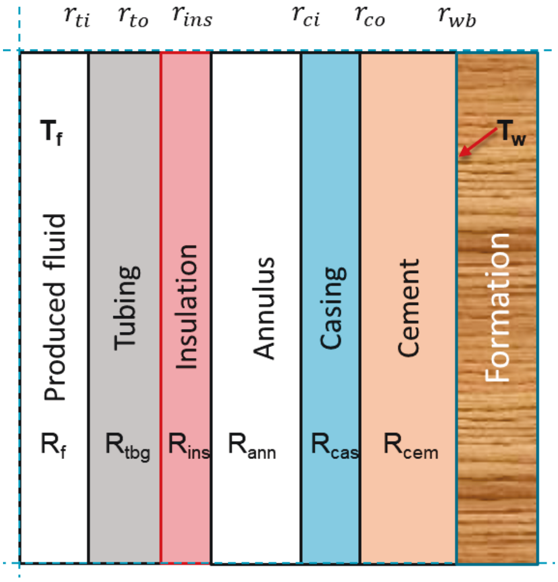


Figure 5: Structure of heat transfer model for wellbore of external insulation of tubing

Figure 5 illustrates the different resistance mentioned in the equation below in the pipe flow the tubing wall, insulation, annulus, casing wall, and cement.

By using the equation of resistances, the overall heat transfer in the wellbore can be expressed as: (Hasan et al. 2002)

$$\frac{1}{U_{to}} = \frac{r_{to}}{r_{ti} * h_f} + \frac{r_{to}\ln(\frac{r_{to}}{r_{ti}})}{k_{tbg}} + \frac{r_{to}\ln(\frac{r_{ins}}{r_{to}})}{k_{ins}} + \frac{r_{to}}{r_{ins}(h_c + h_r)} + \frac{r_{to}\ln(\frac{r_{co}}{r_{ci}})}{k_{cas}} + \frac{r_{to}\ln(\frac{r_{wb}}{r_{co}})}{k_{cem}} \tag{34}$$

Equation (34) was the basis for the model of external insulation for the two cases of oil and gas. The values that differ in the equation between the oil and gas are the liquid/gas convective heat transfer coefficient, annular convective heat transfer coefficient and the annular radiative heat transfer coefficient and well parameters (tubing and casing sizes).

Every insulation material has a specific value of thermal conductivity, which was used in the equation to calculate the overall heat transfer of the well for different insulators and thicknesses. The result will be then used as an input in the software for the simulation part.

3.3 Internal insulation model

In the second case, the insulation material will be installed inside the tubing in order to compare its effectiveness with the outside insulation.

Heat flow resistance from wellbore tubing to formation includes the insulation inside the tubing, the tubing wall, the annulus, casing wall, and cementing behind the casing as illustrated in Figure 6.

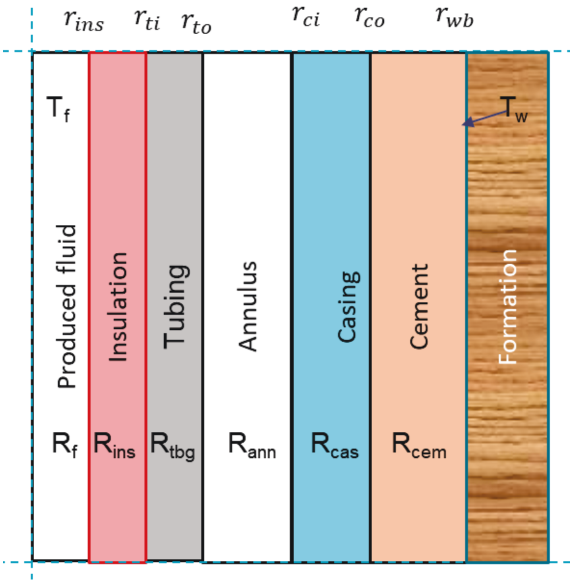


Figure 6: Structure of heat transfer model for wellbore of internal insulation of tubing

The total resistance in the wellbore is expressed by: (Hasan et al. 2002)

$$\mathrm{R_{total}} = (\mathrm{R_f} + \mathrm{R_{tbg}} + \mathrm{R_{ins}} + \mathrm{R_{ann}} + \mathrm{R_{cas}} + \mathrm{R_{cem}}) \tag{35}$$

1. The convection resistance of heat flow near the inner tubing is:

$$\mathrm{R_f} = \frac{1}{2\pi \mathrm{h_f r_{ins}} \Delta \mathrm{L}} \tag{36}$$

2. The conduction resistance of the inside insulation of tubing is:

$$\mathrm{R_{ins}} = \frac{\ln\left(\frac{\mathrm{r_{ti}}}{\mathrm{r_{ins}}}\right)}{2\pi \mathrm{k_{ins}} \Delta \mathrm{L}} \tag{37}$$

3. The conduction resistance of outside tubing insulation is:

$$\mathrm{R_{tbg}} = \frac{\ln\left(\frac{\mathrm{r_{to}}}{\mathrm{r_{ti}}}\right)}{2\pi \mathrm{k_{tbg}} \Delta \mathrm{L}} \tag{38}$$

4. The conduction resistance of the casing is :

$$\mathrm{R_{cas}} = \frac{\ln\left(\frac{\mathrm{r_{co}}}{\mathrm{r_{ci}}}\right)}{2\pi \mathrm{k_{cas}} \Delta \mathrm{L}} \tag{39}$$

5. The conduction resistance of the annulus :

$$\mathrm{R_{ann}} = \frac{1}{2\pi \mathrm{r_{to}} (\mathrm{h_c} + \mathrm{h_r}) \Delta \mathrm{L}} \tag{40}$$

6. The conduction resistance of the cement :

$$\mathrm{R_{cem}} = \frac{\ln\left(\frac{\mathrm{r_{wb}}}{\mathrm{r_{co}}}\right)}{2\pi \mathrm{k_{cem}} \Delta \mathrm{L}} \tag{41}$$

The overall heat transfer is related to the resistance by this equation:

$$\mathrm{R_{total}} = \frac{1}{2\pi \mathrm{r_{to}} \Delta \mathrm{L} \mathrm{U_{to}}} \tag{42}$$

Therefore, by combining the equation (35) to the equation (42) , the overall heat transfer is:

$$\frac{1}{\mathrm{U_{to}}} = \frac{\mathrm{r_{to}}}{\mathrm{r_{ins}} \mathrm{h_f}} + \frac{\mathrm{r_{to}} \ln(\frac{\mathrm{r_{ti}}}{\mathrm{r_{ins}}})}{\mathrm{k_{ins}}} + \frac{\mathrm{r_{to}} \ln(\frac{\mathrm{r_{to}}}{\mathrm{r_{ti}}})}{\mathrm{k_{tbg}}} + \frac{1}{\mathrm{h_c} + \mathrm{h_r}} + \frac{\mathrm{r_{to}} \ln(\frac{\mathrm{r_{co}}}{\mathrm{r_{ci}}})}{\mathrm{k_{csg}}} + \frac{\mathrm{r_{to}} \ln(\frac{\mathrm{r_{wb}}}{\mathrm{r_{co}}})}{\mathrm{k_{cem}}} \tag{43}$$

Equation (43) is implemented in the Excel model used for the calculation of the inside insulation overall heat transfer coefficient. This coefficient is the output for each case of insulation material with its specific thickness. The insulation thickness that can be used in this model depends on the tubing size, which cannot exceed a particular value to avoid production problems and especially the ones from fishing and handling. (Hasan et al. 2002)

3.4 Input data for the simulation

The input data are divided into four parts: geometrical parameters, thermal convective coefficients, and thermal conductivities and overall heat transfer values of the well. Table 4 illustrates the geometrical parameters of the well used for the simulation.

Table 4: Geometrical parameters of the oil well used in the model

Input	Symbol	Value (inch)
Tubing outside diameter	d_{to}	4
Tubing inside diameter	d_{ti}	3.548
Casing inside diameter	d_{ci}	7.511
Casing outside diameter	d_{co}	8.625
Wellbore diameter	d_{wb}	10.625

Table 5 and Table 6 presents the thermal convective and conductivities coefficients used for the calculation of the overall heat transfer coefficient. Table 7 and Table 8 illustrates the results of U coefficients for all the insulation materials for various insulation thicknesses.

Table 5: Input data of thermal convective coefficients for oil well

Convective heat transfer coefficients	Unit	Symbol	Value
Film	W/m²K	h_f	2840
Convection	W/m²K	h_c	567
Radiation	W/m²K	hr	11.35

Table 6: Input data of thermal conductivities for oil well

Thermal conductivities	Unit	Symbol	k-Value
Tubing	W/mK	k_{tbg}	43.2
Insulation	W/mK	k_{ins}	cp. Table 3
Casing	W/mK	k_{cas}	43.2
Cement	W/mK	k_{cem}	1.03

Table 7: U-values for the internal insulation simulation

Internal insulation	Overall heat transfer of the well (W/m²K)						
0.1”	33.4	23.1	11.6	9.0	8.5	6.3	3.9
0.15”	25.6	16.8	8.0	6.2	5.8	4.2	2.6
0.2”	20.7	13.2	6.1	4.6	4.4	3.2	1.9
0.25”	17.2	10.7	4.9	3.7	3.5	2.5	1.5
Insulation material	PPF	CSPI	MW	PUF	FG	MPS	AI

Table 8: U-values for the external insulation simulation

External insulation	Overall heat transfer of the well (W/m²K)						
0.1”	36.9	26.1	13.4	10.5	9.9	7.3	4.6
0.15”	29.3	19.7	9.6	7.4	7.0	5.1	3.1
0.2”	24.4	15.9	7.5	5.8	5.4	3.9	2.4
0.25”	21.0	13.4	6.2	4.7	4.4	3.2	2.0
0.5”	12.7	7.7	3.4	2.6	2.4	1.7	1.0
0.75”	9.3	5.5	2.4	1.8	1.7	1.2	0.7
1”	7.5	4.4	1.9	1.4	1.3	1.0	0.6
1.25”	6.4	3.7	1.6	1.2	1.1	0.8	0.5
Insulation material	PPF	CSPI	MW	PUF	FG	MPS	AI

4 Simulation of thermal insulation of tubing

In this chapter, the effect of the thermal insulation will be evaluated on different parameters such as the production rate, temperature profile and pressure losses along the wellbore.

4.1 Light oil simulation

The simulation was performed for three different types of oil, which are light oil (36 API°), medium oil (26 API°), and heavy crude (16 API°). First, the fluid model used for the simulation was the light oil. Several insulation materials were evaluated in the simulation. For each insulation thickness, the simulation was done for all the materials to see its impact especially on the production rate and the temperature profile of the well and to compare the results. The fluid properties used for light oil simulation are shown in Table 9.

Table 9: Light oil input data in PIPESIM

API grade	36°
Gas oil ratio	500 Scf/STB
Water cut	10%
Gas specific gravity	0.8
Water specific gravity	1.05

The IPR curve and VLP curve of the well are shown in Figure 7. The well deliverability is 7523 bbl/day at 2659 psi.

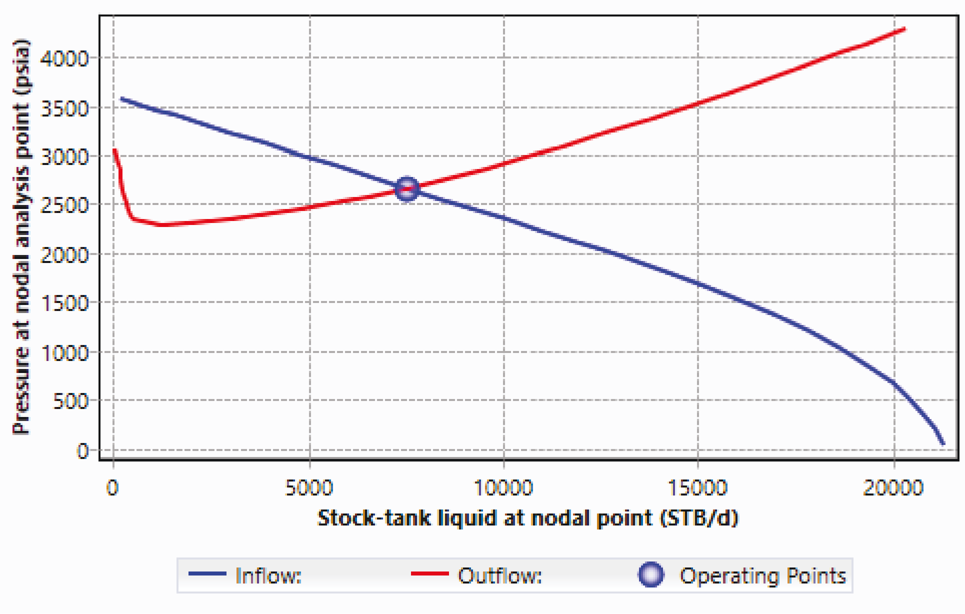
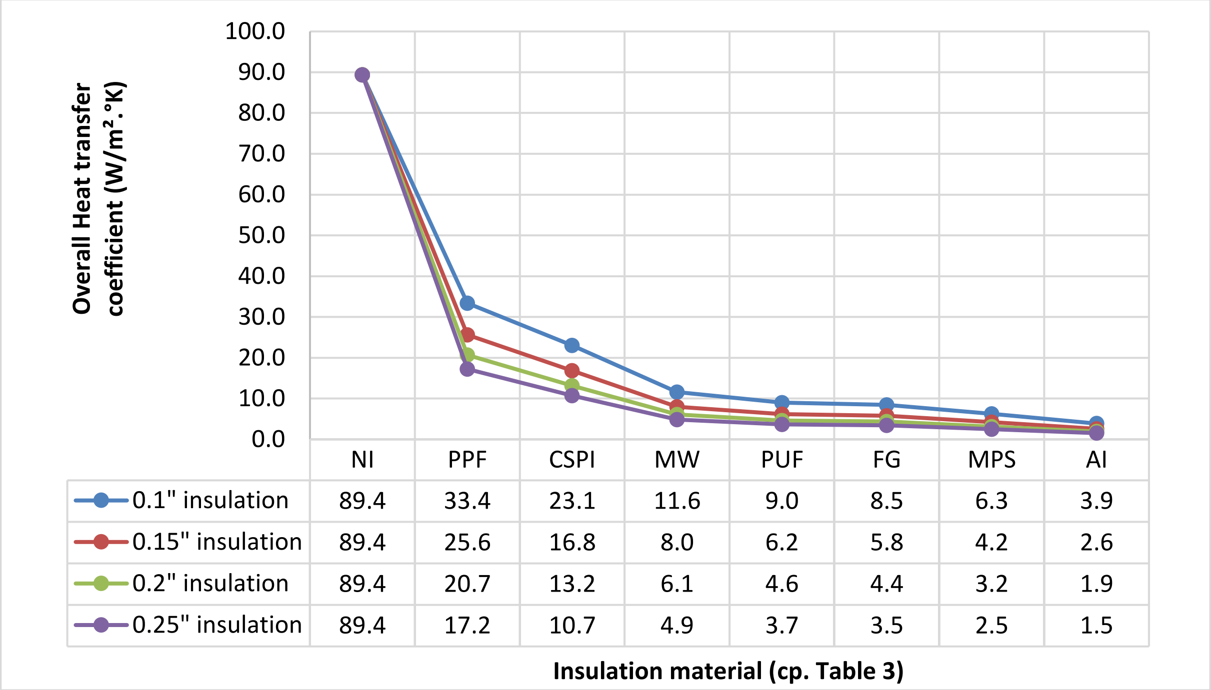


Figure 7: Inflow performance and outflow performance of the well (36°API)

4.1.1 Internal insulation

In this section, the insulation was simulated inside the tubing with a thickness varying between 0.1” and 0.25”. The overall heat transfer is calculated for different insulation materials using the Excel model for inside insulation. The results are shown in Figure 8.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	89.4	33.4	23.1	11.6	9.0	8.5	6.3	3.9
0.15" insulation	89.4	25.6	16.8	8.0	6.2	5.8	4.2	2.6
0.2" insulation	89.4	20.7	13.2	6.1	4.6	4.4	3.2	1.9
0.25" insulation	89.4	17.2	10.7	4.9	3.7	3.5	2.5	1.5

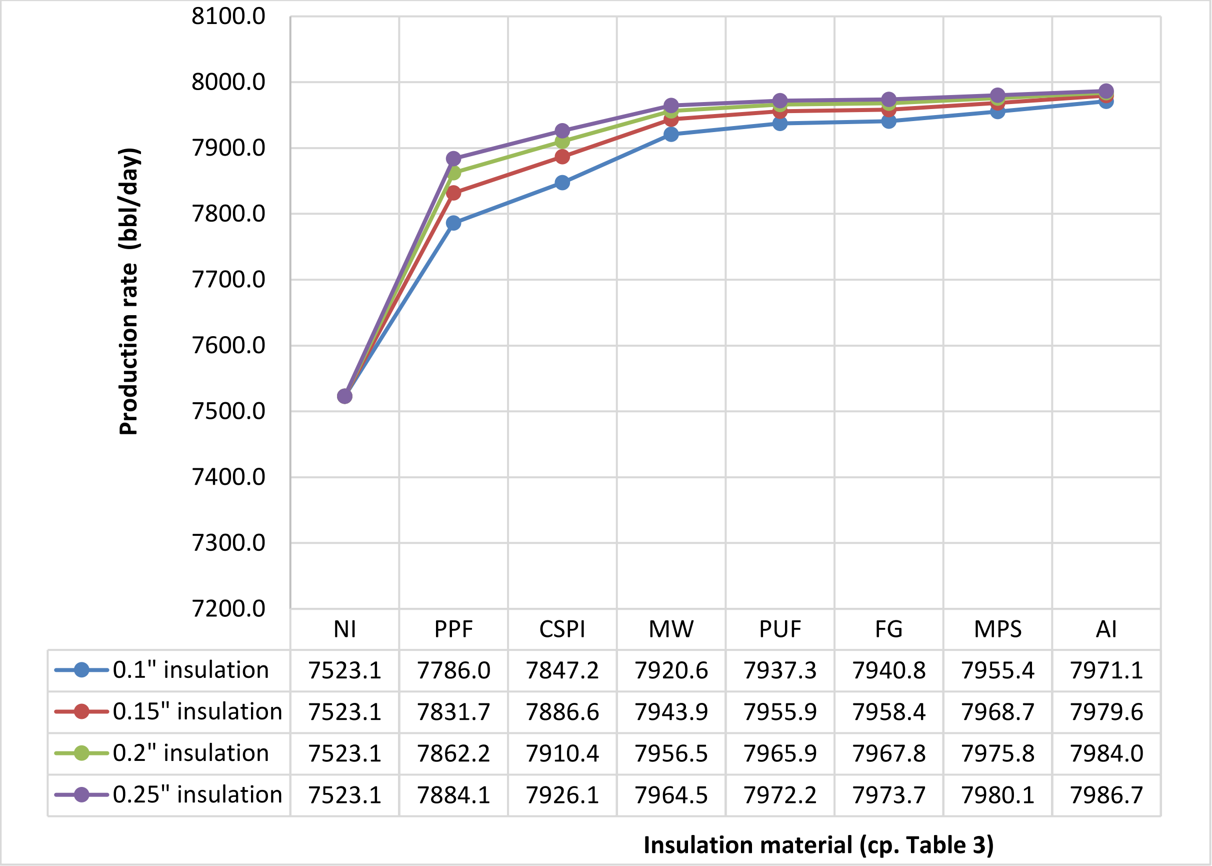
Figure 8 : Overall heat transfer of the well for internal insulation (36°API)

Figure 8 illustrates the overall heat transfer results calculated from the model. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).The overall heat transfer decreases as the thermal conductivity of the insulation material decreases which is shown in the graph.

When the insulation thickness increases, the overall heat transfer of the well decreases more and more. Some insulation materials were highly affected by the increase of insulation thickness such as polypropylene foam where the overall heat transfer has been reduced to around the half between 0.1” and 0.25”. The insulation materials having the lowest thermal conduction were less affected by the increase in insulation thickness. For instance, the overall heat transfer of aerogel has been reduced from 3.8 W/m²K (0.1” thickness) to 1.5 W/m²K (0.25” thickness).

The overall heat transfer of the well was reduced more by the inside insulation than the external insulation which means that internal insulation is more efficient in conserving the heat than external insulation.

The calculated overall heat transfer coefficients are implemented in PIPESIM software in order to perform the simulation for the different cases. The production rate results are shown in Figure 9 for seven insulation materials with four different insulation thicknesses.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	7523.1	7786.0	7847.2	7920.6	7937.3	7940.8	7955.4	7971.1
0.15" insulation	7523.1	7831.7	7886.6	7943.9	7955.9	7958.4	7968.7	7979.6
0.2" insulation	7523.1	7862.2	7910.4	7956.5	7965.9	7967.8	7975.8	7984.0
0.25" insulation	7523.1	7884.1	7926.1	7964.5	7972.2	7973.7	7980.1	7986.7

Figure 9: Production rate results of internal insulation (36°API)

Figure 9 shows the production rate results in case of internal insulation of tubing. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).

For 0.1” thickness, the production has increased from 7523 bbl/day to a minimum of 7786 bbl/day in case of polypropylene foam and to a maximum of 7971.1 bbl/day in case of aerogel. Therefore, the increase percentage of production has varied between 3.5% and 5.9 %.

Increasing the insulation thickness to 0.15” has risen the production rate as well. The production gain has ranged between 4.1% and 6.07%.

For 0.2” internal insulation, the production has increased by a minimum of 4.5% and a maximum of 6.07%. The highest production gains from the internal insulation were obtained for a 0.25” insulation thickness. The increase percentage has varied between 4.8% (polypropylene foam) and 6.16% (aerogel insulation).

It is remarkable that the lowest production gain was obtained in case of polypropylene foam due to having the highest thermal conductivity among the materials used. The highest increases were achieved for the insulation materials having the lowest thermal conductivities such as microporous silica, aerogel…

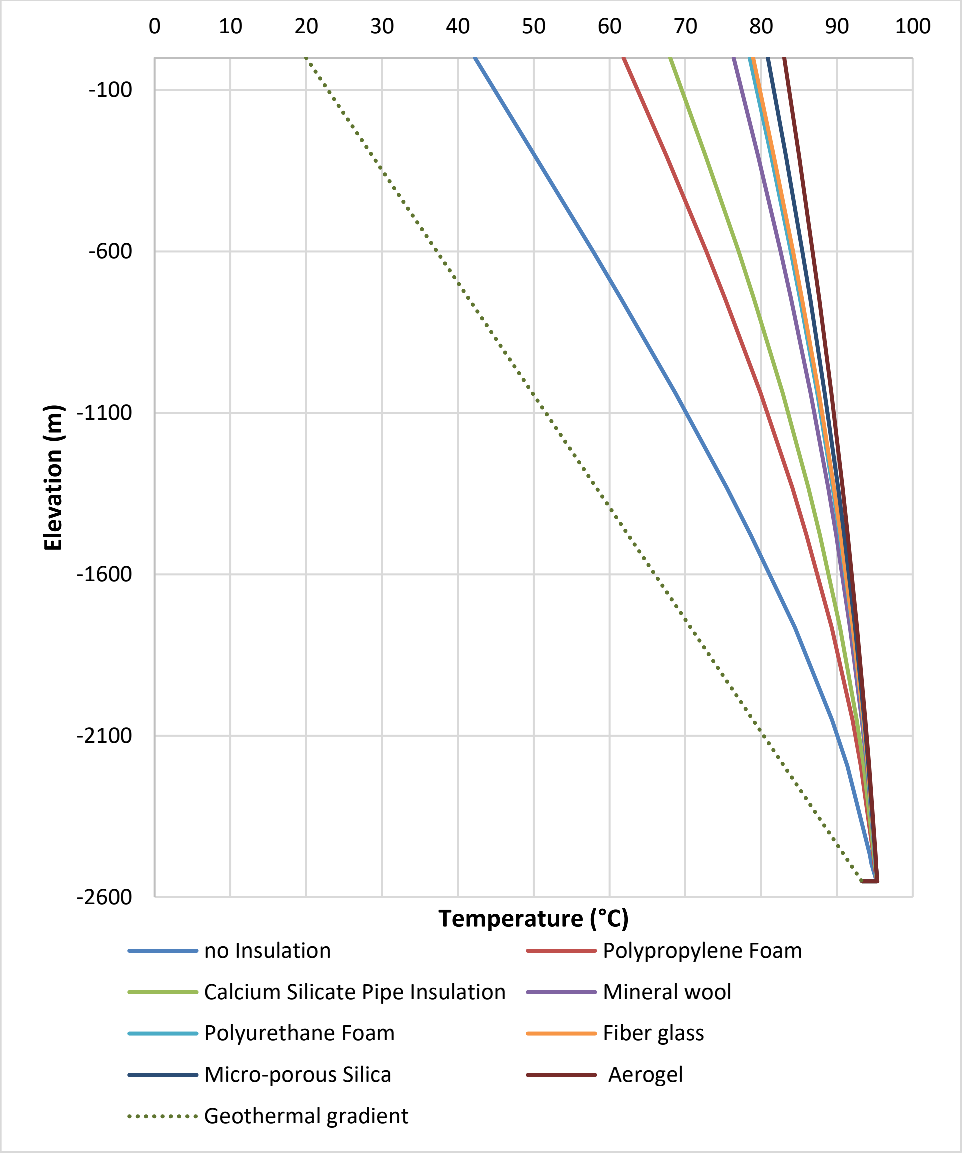


Figure 10: Temperature profile of the well for 0.1" internal insulation (36° API)

The next output result from the simulation is the temperature profile of the well, which was plotted for different insulation materials in case of using the same thickness. Figure 10 shows the temperature profile in case of 0.1” internal insulation of the tubing.

The internal insulation of tubing as shown in Figure 10 affected the temperature profile of the well. The temperature has decreased significantly in the absence of insulation. However, the insulation material has reduced the temperature losses in the well. For instance, mineral wool has conserved 34°C more than the case without insulation. The temperature profile has changed from one type of insulation to another due to the difference of thermal conductivities between the materials. The temperature losses have also decreased by different percentages. The minimum preservation was 19.6°C in case of polypropylene foam, and the maximum was 42°C in case of aerogel where the temperature has dropped by only 10°C from the reservoir to the surface.

Thus, internal insulation can reduce the temperature losses, which can prevent the formation of the precipitations in the tubing and the surface facilities.

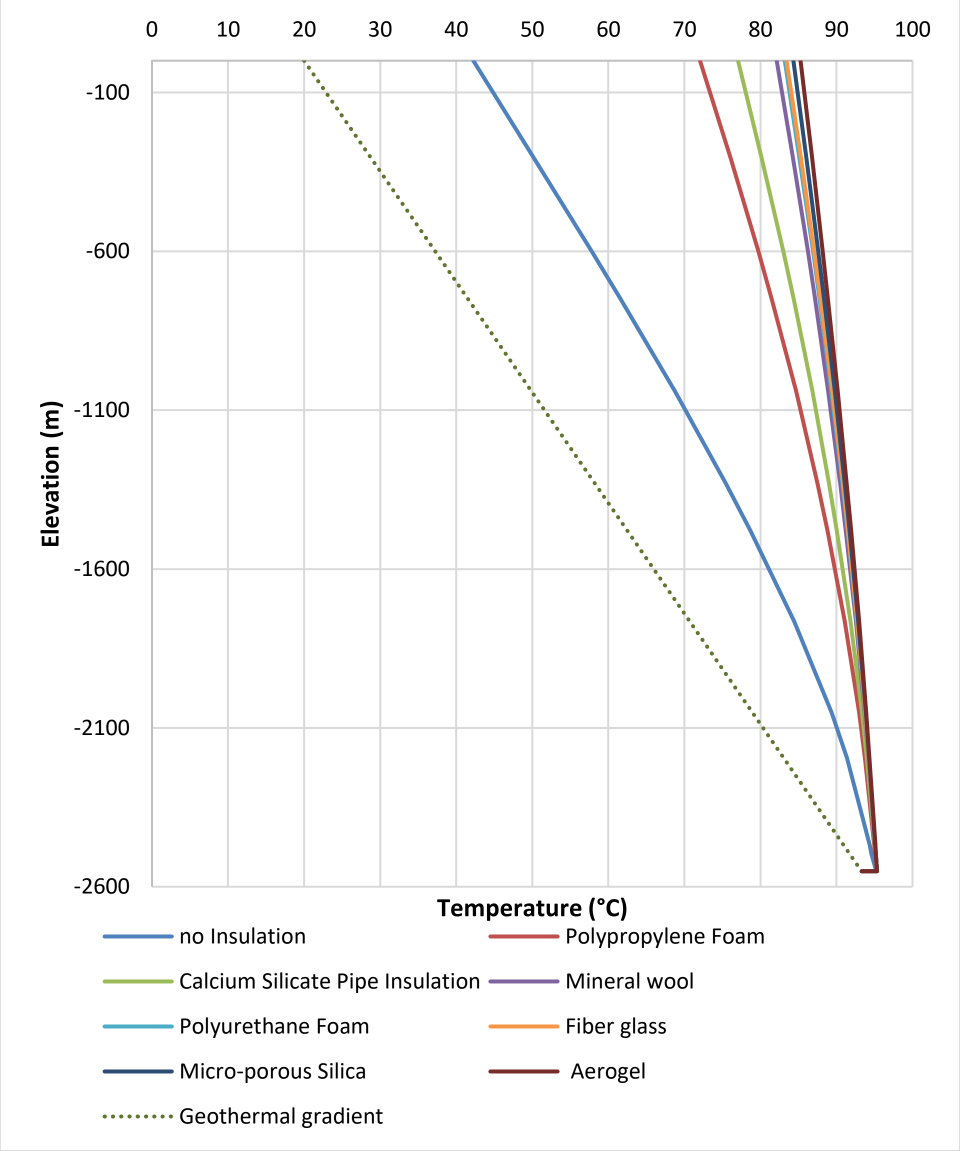


Figure 11: Temperature profile of the well for 0.25" internal insulation (36 °API)

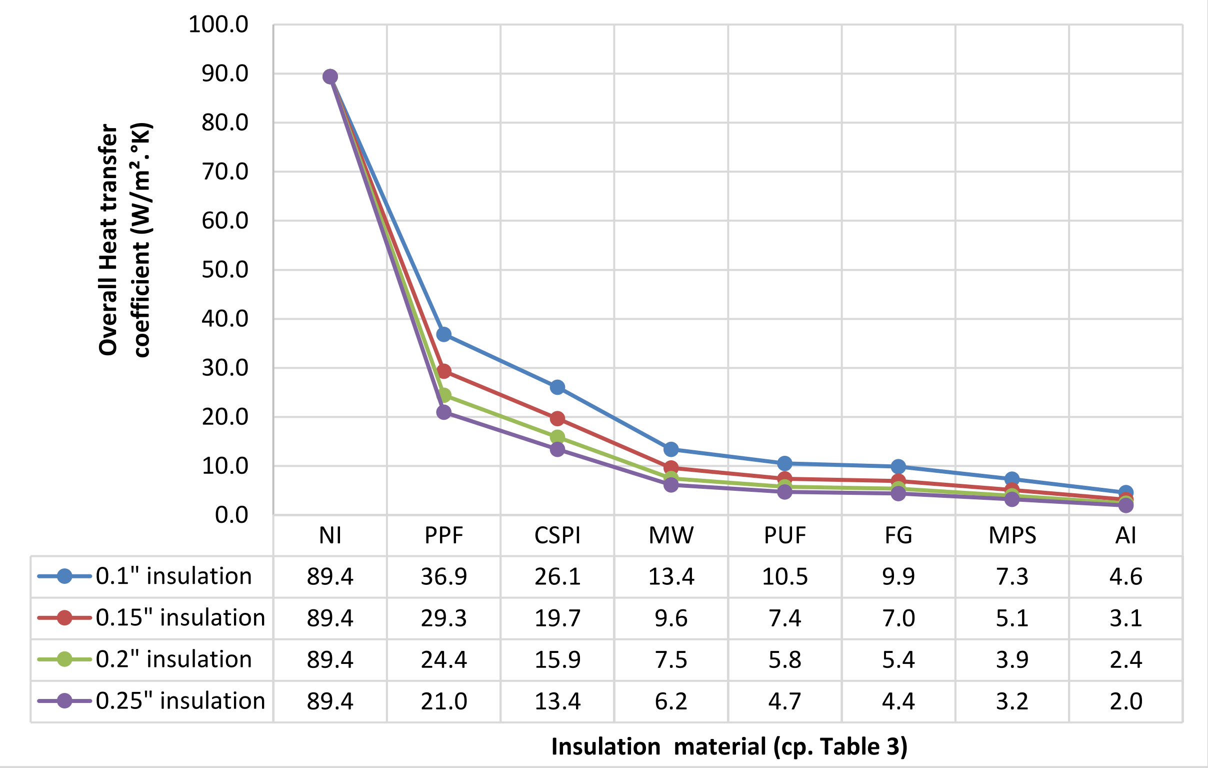
It is noticeable that the increase of thickness has affected the temperature profile as the heat losses have decreased in comparison to the results from Figure 11.

The lowest temperature decline was obtained for the highest insulation thickness. For example, the output temperature has increased from 61°C to 72°C in case of increasing the thickness of polypropylene foam from 0.1” to 0.25”. To sum up, the output temperature for this case has varied between 72°C to 85°C, which is the highest preservation of temperature achieved in case of inside insulation.

Internal insulation has shown less temperature losses than external insulation. Therefore, inside insulation could be a better option in case of using an insulation thickness that does not exceed 0.25”. For thickness higher than 0.25”, the insulation will be evaluated only externally due to size limitations inside the tubing.

4.1.2 External insulation

The insulation was simulated when installed outside the tubing. The values of thickness used are ranging between 0.1” and 0.25”. In order to run the simulation in PIPESIM, the overall heat transfer of the well was calculated for each insulation thickness of each material by using the Excel model of external insulation. The output results are shown in Figure 12.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	89.4	36.9	26.1	13.4	10.5	9.9	7.3	4.6
0.15" insulation	89.4	29.3	19.7	9.6	7.4	7.0	5.1	3.1
0.2" insulation	89.4	24.4	15.9	7.5	5.8	5.4	3.9	2.4
0.25" insulation	89.4	21.0	13.4	6.2	4.7	4.4	3.2	2.0

Figure 12: Overall heat transfer of the well for external insulation (36°API)

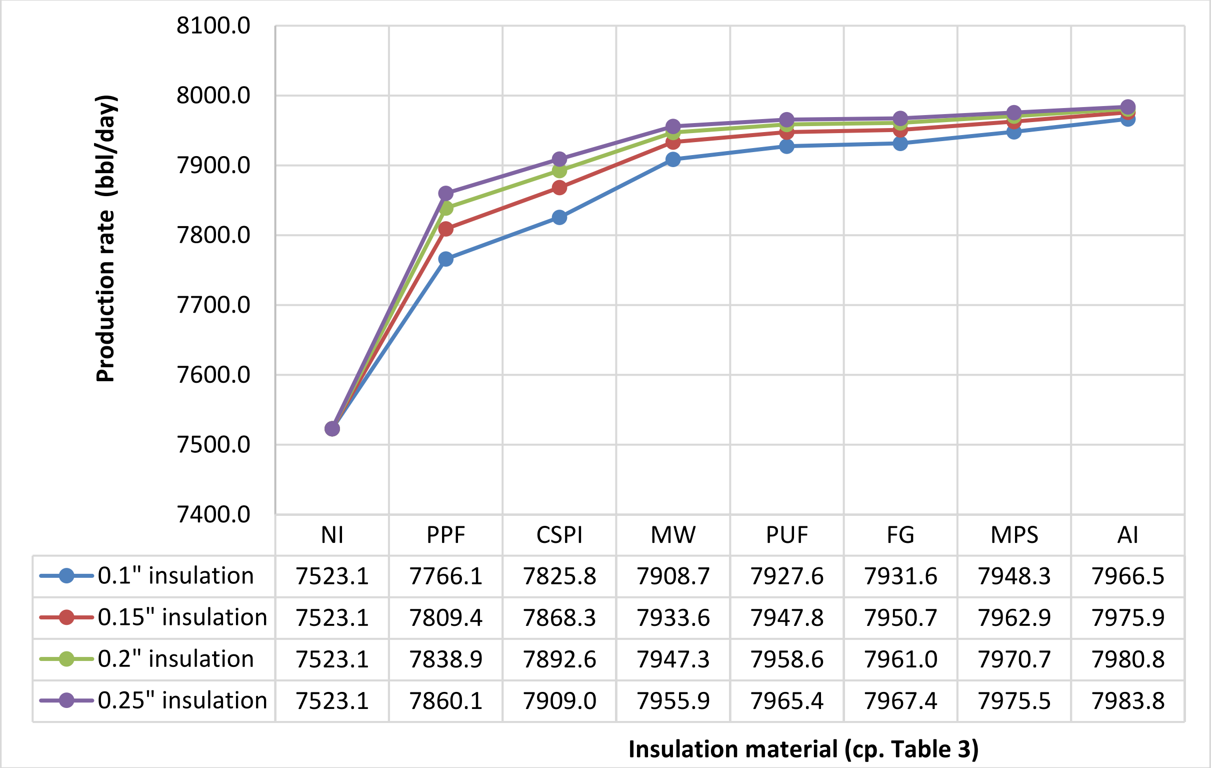
Figure 12 illustrates how the overall heat transfer was affected by adding outside insulation to the tubing. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).

Without insulation, the global heat transfer of the well was 89.3 W/m²K which was the highest value compared to the other insulation material. The overall heat transfer has started to decrease as an insulation material was implemented outer the production tubing

For 0.1” insulation, the minimum decrease was obtained in case of polypropylene foam with a value of 36.8 W/m²K that is 2.5 times less than without insulation. The overall heat transfer decreases more and more as the thermal conductivity of the insulation material decrease. Aerogel has the lowest thermal conductivity of the insulation materials simulated. Therefore, the maximum decline when using an insulation thickness of 0.1” was 4.5 W/m²K in case of using aerogel.

The insulation was increased to 0.15” to observe its effects on the heat transfer. Based on the results illustrated in Figure 12, the overall heat transfer values for each insulation material has decreased more as the insulation thickness has increased. The range of values was between 24.4 W/m²K in case of polypropylene foam and 3.1 W/m²K in case of aerogel.

The overall heat transfer values were also calculated for 0.2” and 0.25” insulation thickness. As shown in the graph, the overall heat transfer of the well decreases as the insulation thickness increases. For instance, the best results were obtained in case of 0.25” external insulation where the overall heat transfer was reduced by around 4.5 times less from 89.3 to 21 W/m²K. The overall heat transfer decreases to 13.3 W/m²K in case of calcium silicate and 6.1 W/m²K in case of mineral wool. The coefficients of heat transfer were less than 5 W/m²K for the rest of insulation materials, which are the polyurethane foam, the fiberglass, and the microporous silica. The minimum overall heat transfer value for 0.25” thickness was 1.9 W/m²K in case of aerogel, which is 45 times less than the case of no insulation. Therefore, adding outside insulation will result in reducing the heat losses in the wellbore.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	7523.1	7766.1	7825.8	7908.7	7927.6	7931.6	7948.3	7966.5
0.15" insulation	7523.1	7809.4	7868.3	7933.6	7947.8	7950.7	7962.9	7975.9
0.2" insulation	7523.1	7838.9	7892.6	7947.3	7958.6	7961.0	7970.7	7980.8
0.25" insulation	7523.1	7860.1	7909.0	7955.9	7965.4	7967.4	7975.5	7983.8

Figure 13 : Production rates of the well for external insulation (36°API)

The overall heat transfer results were implemented in PIPESIM to determine its effects on the production rate and the temperature profile of the light oil well. The production rate results are illustrated in Figure 13 for different isolation materials and for different insulation thickness that varies between 0.1” and 0.25”. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).

The production rate of the well without insulation was 7523.1 bbl/day. Adding an insulation layer of 0.1” of polypropylene foam outside the tubing has increased the production from 7523 bbl/day to 7766.1 bbl/day, which is 2.3% increase. The production has increased more when the overall heat transfer of the well has decreased. The maximum increase was 7969.5 bbl/day in case of aerogel due to having the lowest overall heat transfer among the insulation materials. Therefore, the increase percentage in case of 0.1” was between 2.3% and 5.5%.

When the insulation thickness was raised to 0.15”, the production rate has increased in comparison to 0.1” thickness. The production gain for 0.15” was by a minimum of 3.2% for polypropylene foam and a maximum of 5.9% for aerogel.

In case of using 0.2” outside insulation, the production rate has varied between 7838.9 bbl/day and 7980.8 bbl/day. Based on the results from 0.15”, the aerogel still have the highest production rate, but it increased only by 5 bbl/day. However, the gain obtained in case of calcium silicate was 14bbl/day. Therefore, the amount of increase in liquid rate can be seen more for insulation materials with greater thermal conductivities. Besides, the results always show that the production rate increases when the overall heat transfer decreases.

The maximum increase in this simulation was obtained for an insulation thickness of 0.25”, where the production rate reached the highest value for every type of insulation material. The minimum value of production rate was 7866bbl/day in case of polypropylene foam, which has increased by 106bbl/day in comparison to using 0.1” thickness. The maximum value of production rate was 7983.8 bbl/day of oil in case of aerogel. Therefore, the production gain from 0.25” was varying between 4.4% and 6.1%.

To sum up, installing outside insulation in light oil well has a thickness between 0.1” and 0.25” has provided an increasing percentage in production between 2.3% to 6.1%.

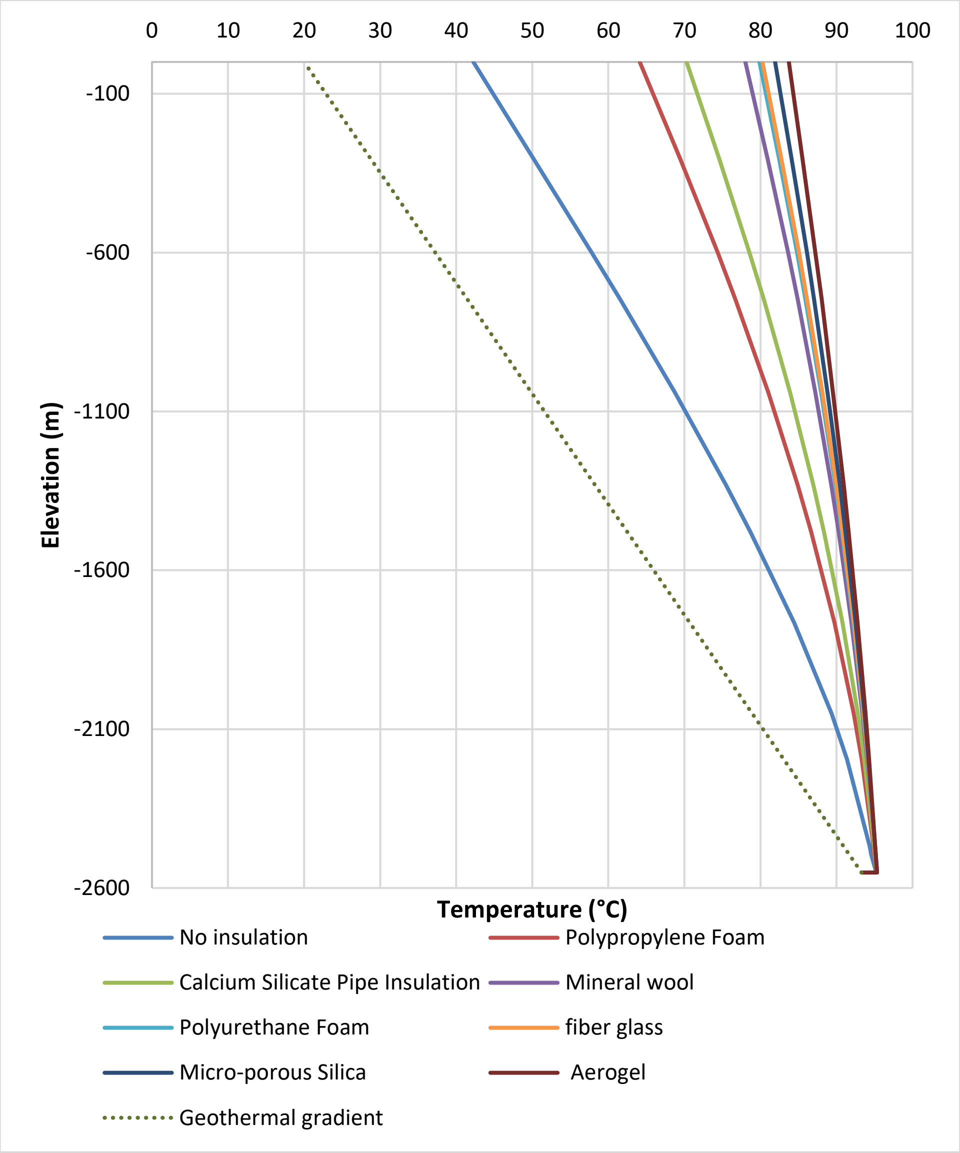


Figure 14: Temperature profile of the well for 0.1” external insulation (36°API)

In case of no insulation, the temperature has dropped from 95°C to 42°C, which is 53°C drop. The temperature losses had decreased significantly, as an insulation material was applied outside the tubing. The maximum temperature drop in presence of insulation was from 95°C to only 64°C.

The temperature losses has decreased as the thermal conductivity decrease from one insulation material to another. For instance, the temperature has dropped from 95°C to only 70°C in case of calcium silicate while it has dropped to 80°C in case of polyurethane foam due to the overall heat transfer coefficients difference.

Therefore, 0.1” external insulation will preserve a minimum of 22°C in case of polypropylene foam and a maximum of 42°C in case of aerogel in comparison to no insulation case.

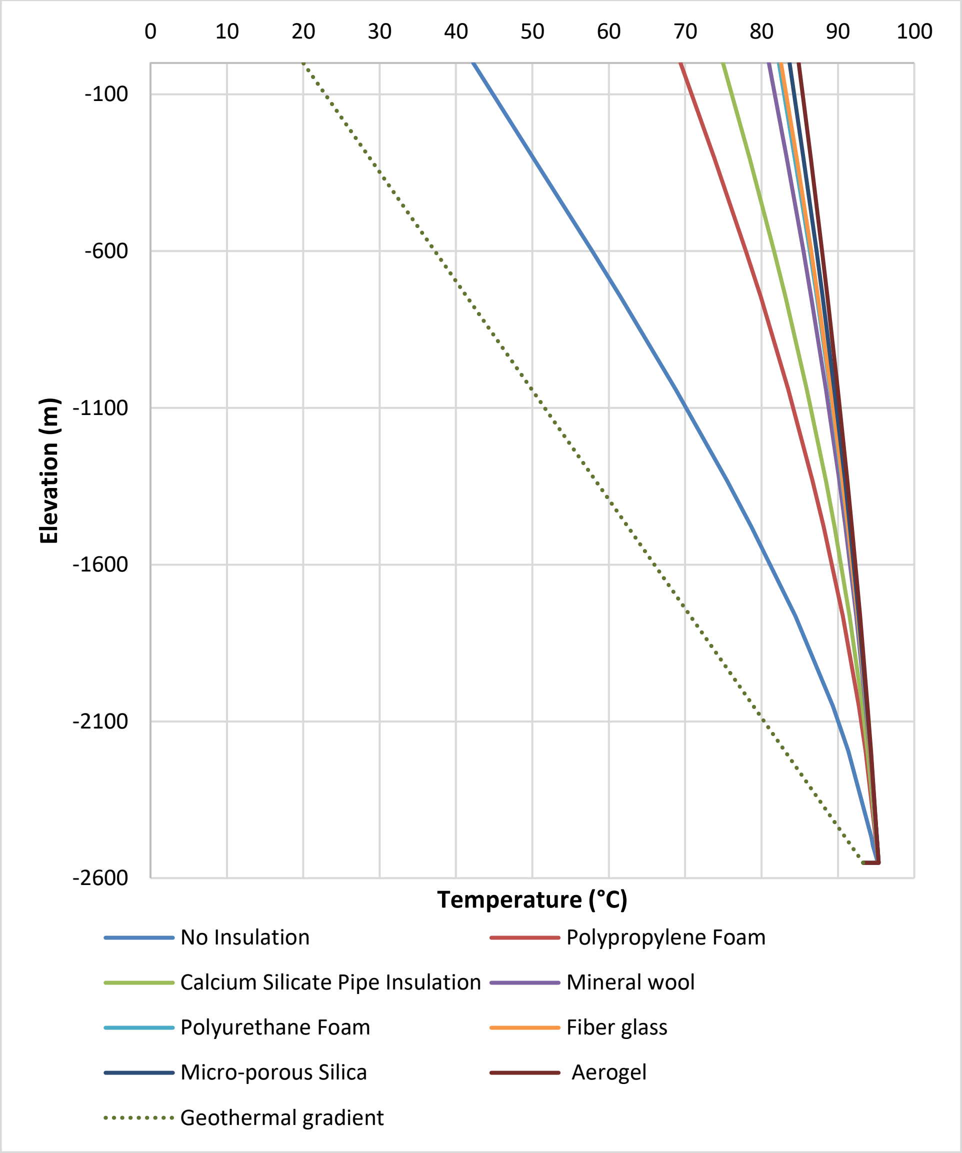


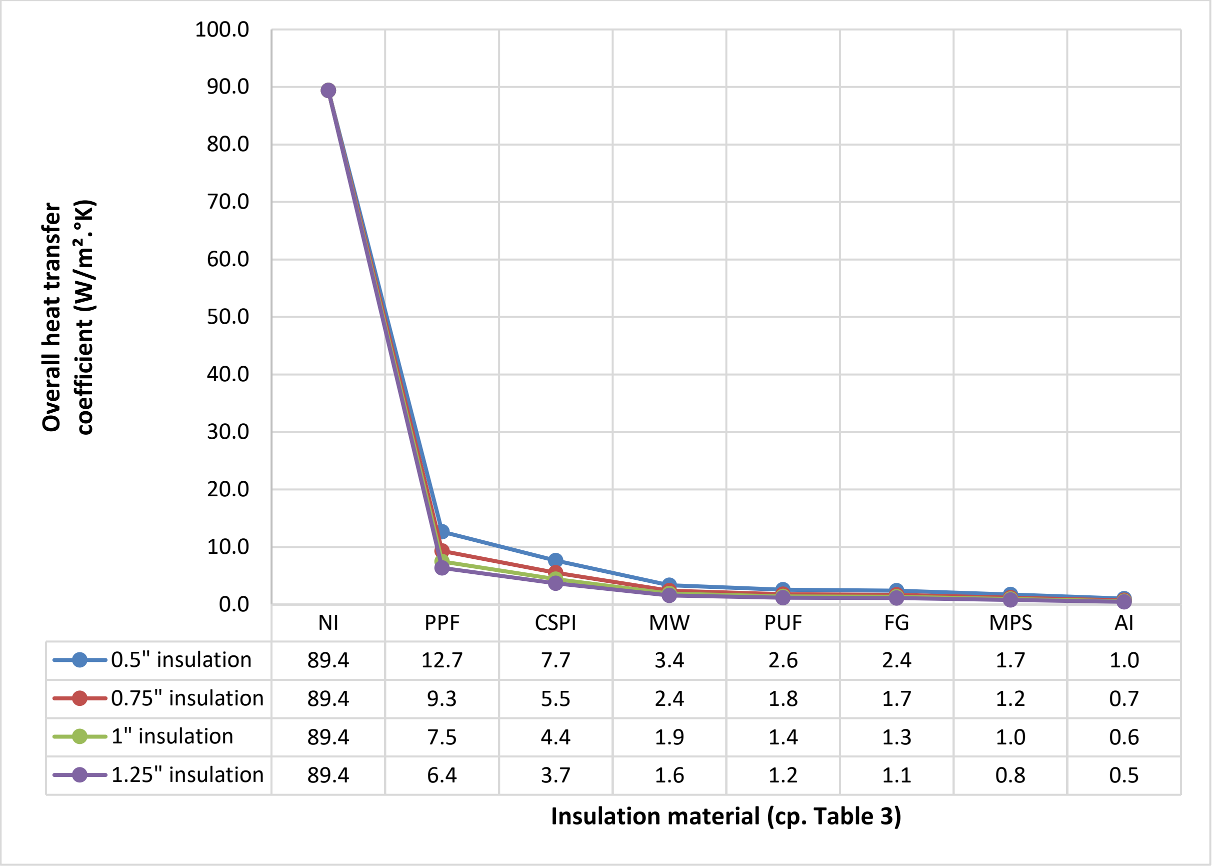
Figure 15: Temperature profile of the well for 0.25" external insulation (36°API)

Figure 15 illustrates the temperature profiles for different materials with 0.25” insulation thickness. Increasing the insulation thickness to 0.25” has reduced more the temperature losses in the well. For instance, the temperature has dropped from 95°C to 69.4°C in case of polypropylene foam which has increased by 5°C compared to using a thickness of 0.15”.

Therefore, increasing the insulation thickness will preserve more heat and reduce more the temperature losses occurring along the well. The conservation of temperature in case 0.25” is between a minimum of 27°C and a maximum of 84.8°C.

4.1.3 Extended external insulation

In this section, the external insulation will be applied outside the tubing with a thickness varying from 0.5” to 1.25”. First, the overall heat transfer for the different cases is calculated using the Excel model. The results are shown in Figure 16.



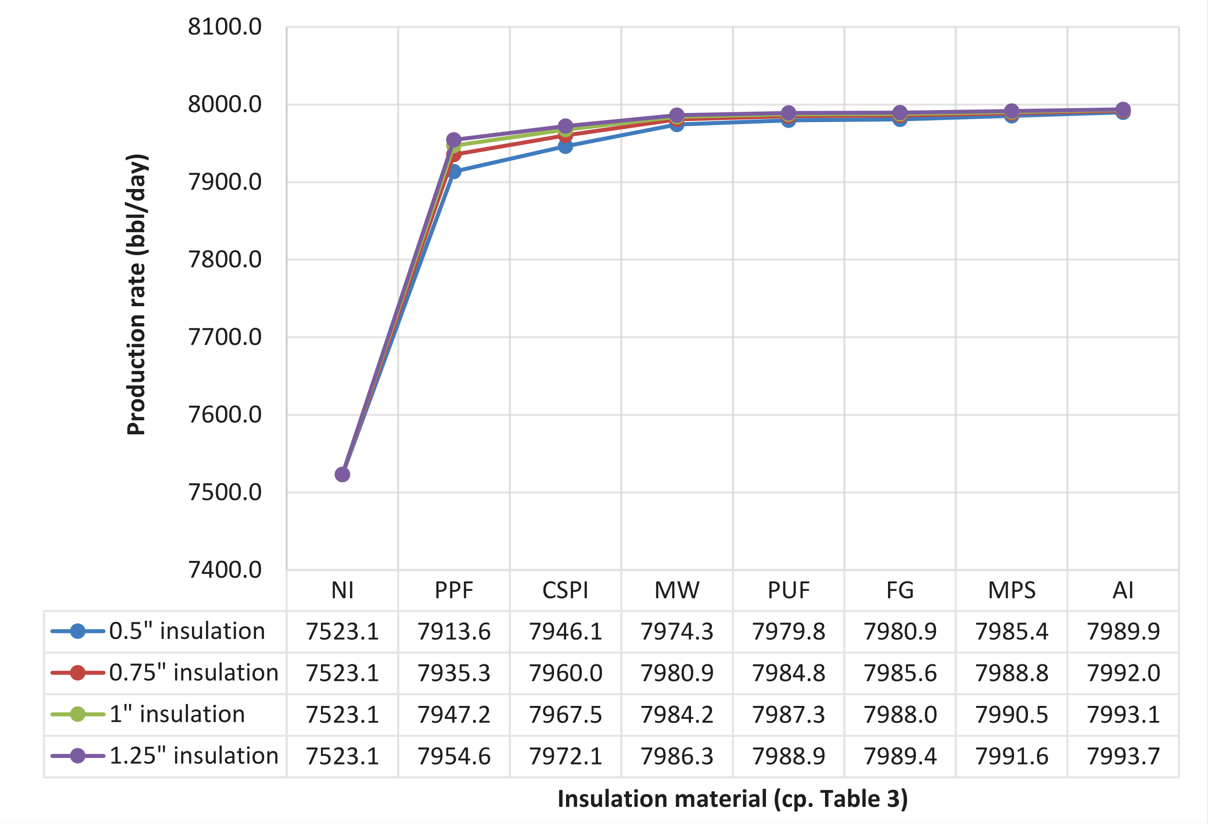
	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.5" insulation	89.4	12.7	7.7	3.4	2.6	2.4	1.7	1.0
0.75" insulation	89.4	9.3	5.5	2.4	1.8	1.7	1.2	0.7
1" insulation	89.4	7.5	4.4	1.9	1.4	1.3	1.0	0.6
1.25" insulation	89.4	6.4	3.7	1.6	1.2	1.1	0.8	0.5

Figure 16: Overall heat transfer of the well for extended external insulation (36 °API)

The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18). Figure 16 shows the values of overall heat transfer for each insulation material for different thicknesses. It is observed that the overall heat transfer decrease as the thermal conductivity decrease. Figure 16 also illustrates that the difference between the values for the same thickness is reduced.

It is remarkable that the overall heat transfer has decreased by around two times from 0.5” to 1.25” insulation thickness, which will have an impact on the heat losses and the production rate of the well.

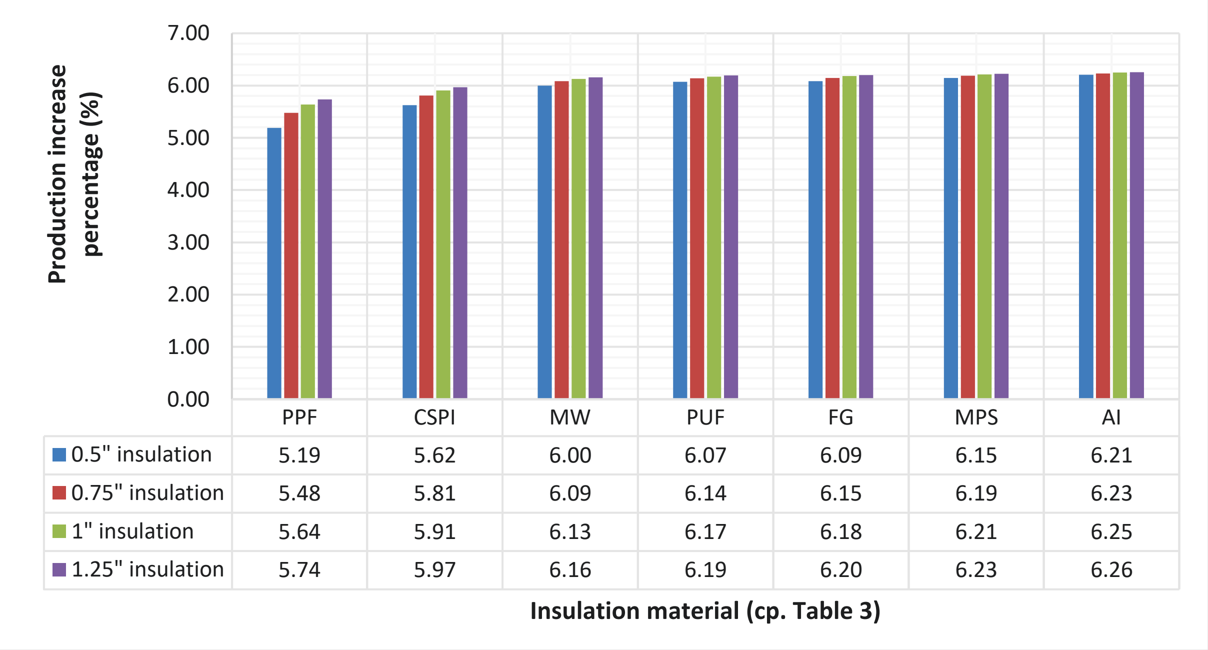
The results shown in Figure 16 are implemented on PIPESIM in order to see their effect on the output results generated from the simulation. The production rate results are shown in Figure 17.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
● 0.5" insulation	7523.1	7913.6	7946.1	7974.3	7979.8	7980.9	7985.4	7989.9
● 0.75" insulation	7523.1	7935.3	7960.0	7980.9	7984.8	7985.6	7988.8	7992.0
● 1" insulation	7523.1	7947.2	7967.5	7984.2	7987.3	7988.0	7990.5	7993.1
● 1.25" insulation	7523.1	7954.6	7972.1	7986.3	7988.9	7989.4	7991.6	7993.7

Figure 17: Production rate results of extended external insulation (36 °API)

The polypropylene foam and calcium silicate were more affected by increasing the insulation thickness. However, the increase of production was minimal for the rest of insulation materials despite having high insulation thickness. Thus, increasing the insulation thickness had more impact on insulation materials with higher thermal conductivities.



	PPF	CSPI	MW	PUF	FG	MPS	AI
■ 0.5" insulation	5.19	5.62	6.00	6.07	6.09	6.15	6.21
■ 0.75" insulation	5.48	5.81	6.09	6.14	6.15	6.19	6.23
■ 1" insulation	5.64	5.91	6.13	6.17	6.18	6.21	6.25
■ 1.25" insulation	5.74	5.97	6.16	6.19	6.20	6.23	6.26

Figure 18: Production increase percentage for extended external insulation (36°API)

Figure 18 shows the increase percentage of the production rate of the well for different insulation materials and thicknesses. For 0.5” external insulation, the percentage has varied between 5.19% and 6.21%. Increasing the thickness to 0.75” has affected especially the polypropylene foam and calcium silicate insulation as illustrated in the graph. The highest production gain was obtained in case of 1.25” external insulation where the percentage has varied between 5.74% and 6.26%.

Based on Figure 18, it is noticeable that the optimum insulation thickness was reached for some materials such as micro-porous silica (1.25”) and aerogel (1”).

Temperature distributions in the well were plotted for different types of insulation materials and thicknesses varying between 0.5” and 1.25”. Figure 19 and Figure 20 shows the temperature profiles for 0.5” and 1.25”.

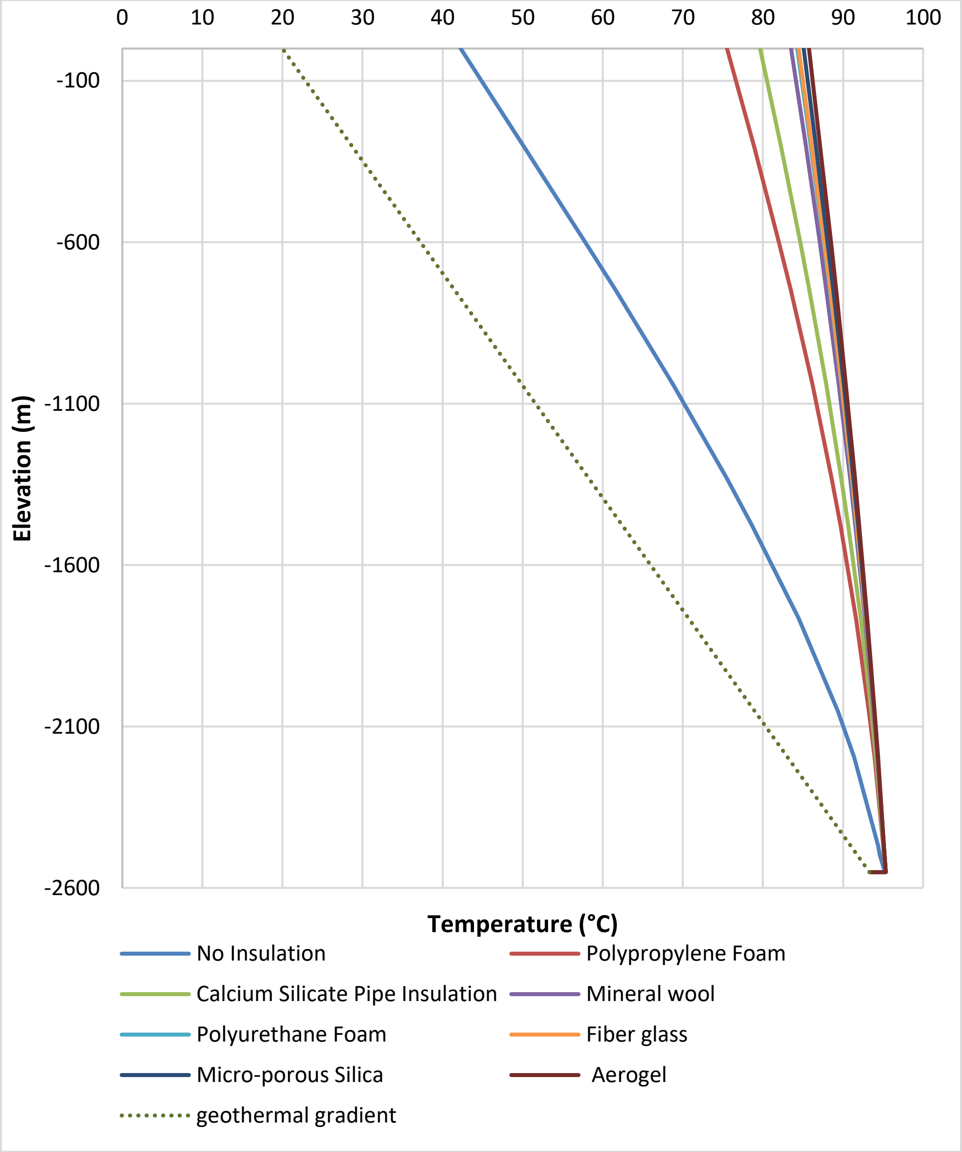


Figure 19: Temperature profile of the well for 0.5" external insulation (36°API)

Insulating the tubing with 0.5”, guarantees a minimum of 75.5°C and a maximum of 85.7°C output temperature. According to Figure 19, it is observed that the mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel have nearly the same trend but with a very little difference. Therefore, the selection of insulation material will be based in this case on the production rate and costs.

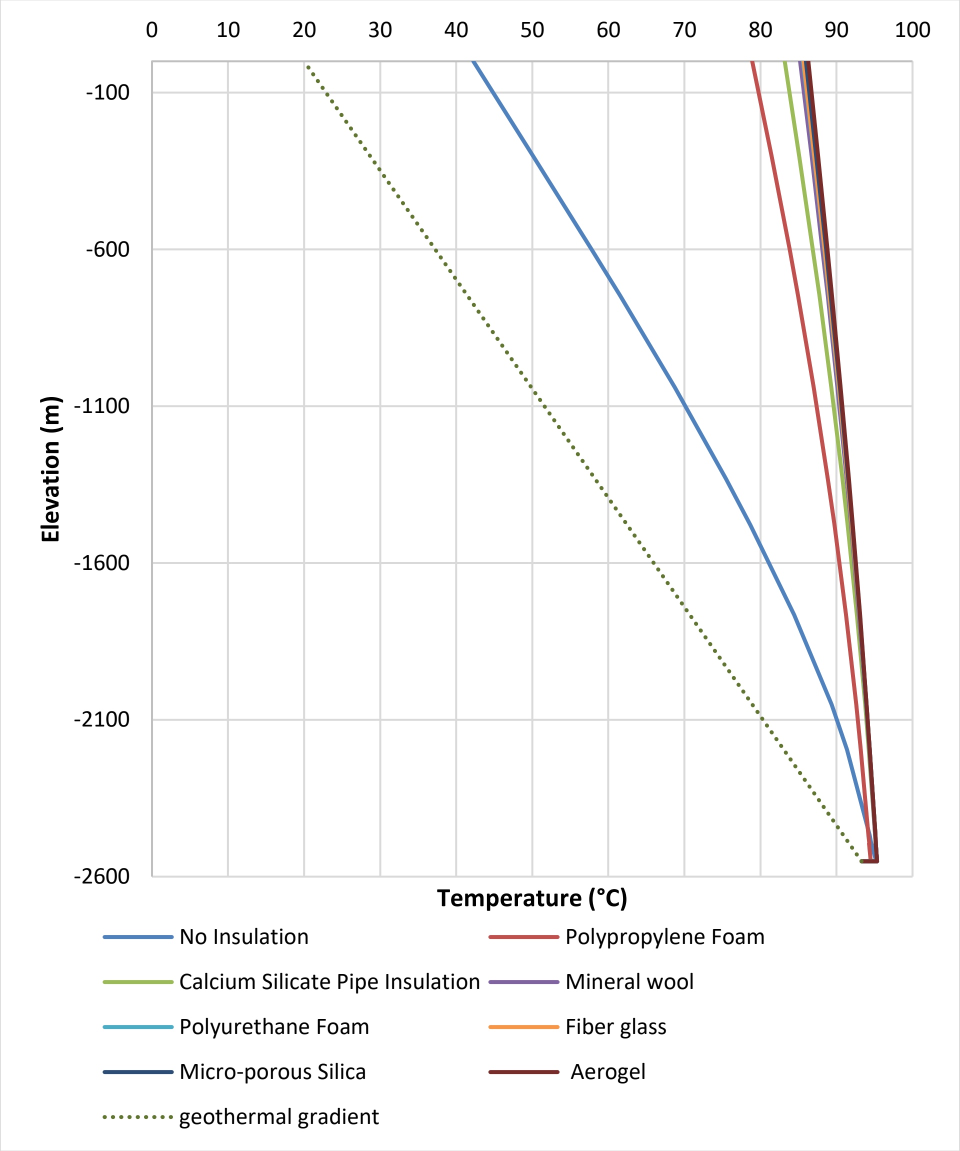


Figure 20: Temperature profiles of the well for 1.25" external insulation (36°API)

The insulation thickness has been increased to a maximum value of 1.25”. In fact, the output temperature results for all materials were more than 80°C, which has occurred only in case of using 1.25”. Increasing thickness has reduced the temperature losses for all the materials. The temperature gain when changing the thickness has increased with high thermal conductivity insulators. For instance, output temperature of polypropylene foam, which has the highest thermal conductivity, has increased from 75.5°C to 80.5°C. However, the output temperature of aerogel has increased by only 0.5°C when increasing the insulation from 0.5” to 1.25”.

4.2 Medium oil simulation

In this section, the simulation will be performed for medium oil production with 26 API°. The materials used for tubing insulation, in this case, are the polypropylene foam, calcium silicate insulation, mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel. The insulation thickness was varying between 0.05” to 1.25” for outside isolation and between 0.05” to 0.25” for inside isolation.

All the insulation materials will be simulated for different thicknesses to see their impact on the overall heat transfer, the production rate and the temperature profile of the well. The same geometrical parameters shown in Table 10 are used in the medium oil. The fluid properties are changed in comparison to light oil model.

Table 10: Fluid properties for medium oil simulation

Stock Tank Properties		Value in PIPESIM model
Water cut (%)		10
Gas oil ratio (Scf/STB)		500
Gas specific gravity (-)		0.64
Water specific gravity (-)		1.02
API (°Api)		26°
Specific heat capacity (kJ/kgK)	Gas	2.3
	Oil	1.88
	water	4.18
Thermal conductivity (W/mK)	Gas	0.03
	Oil	0.13
	Water	0.6

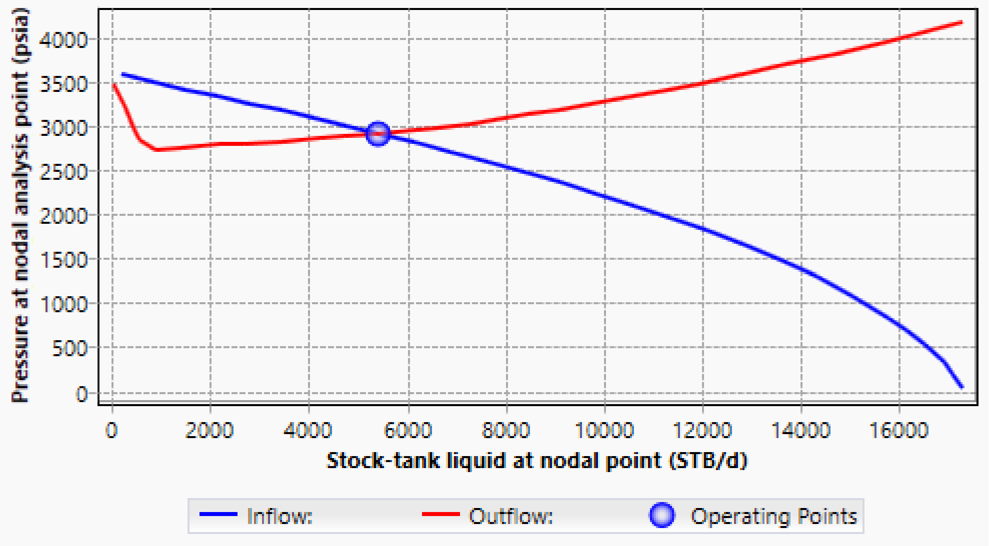
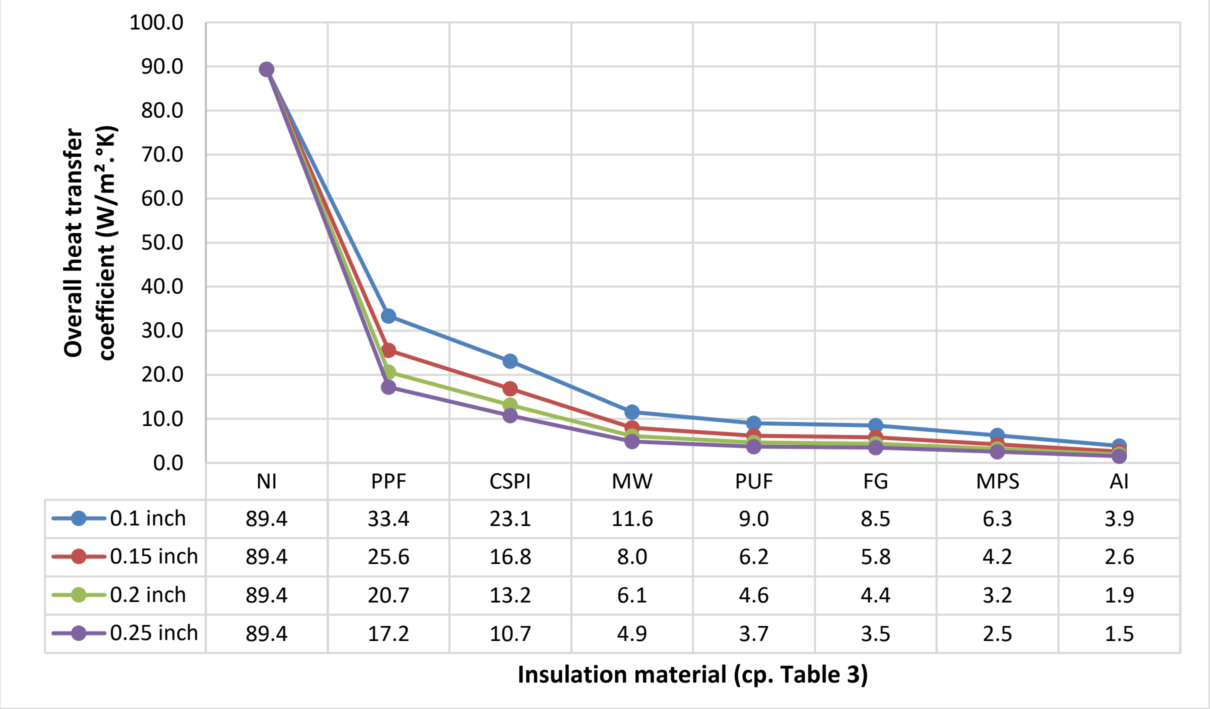


Figure 21: IPR and VLP of the well (26°API)

Figure 21 illustrates the inflow performance and the vertical lift performance of the well at normal conditions where there is no insulation of the tubing. The initial operating point production is 5408 bbl/day at 2910 psi.

4.2.1 Internal insulation

In this part, the insulation is assumed inside the tubing and is evaluated for thicknesses varying from 0.1” to 0.25”. The first step in the simulation is to calculate the overall heat transfer coefficient of the well to implement it in the PIPESIM software. The results of calculations are shown in Figure 22.

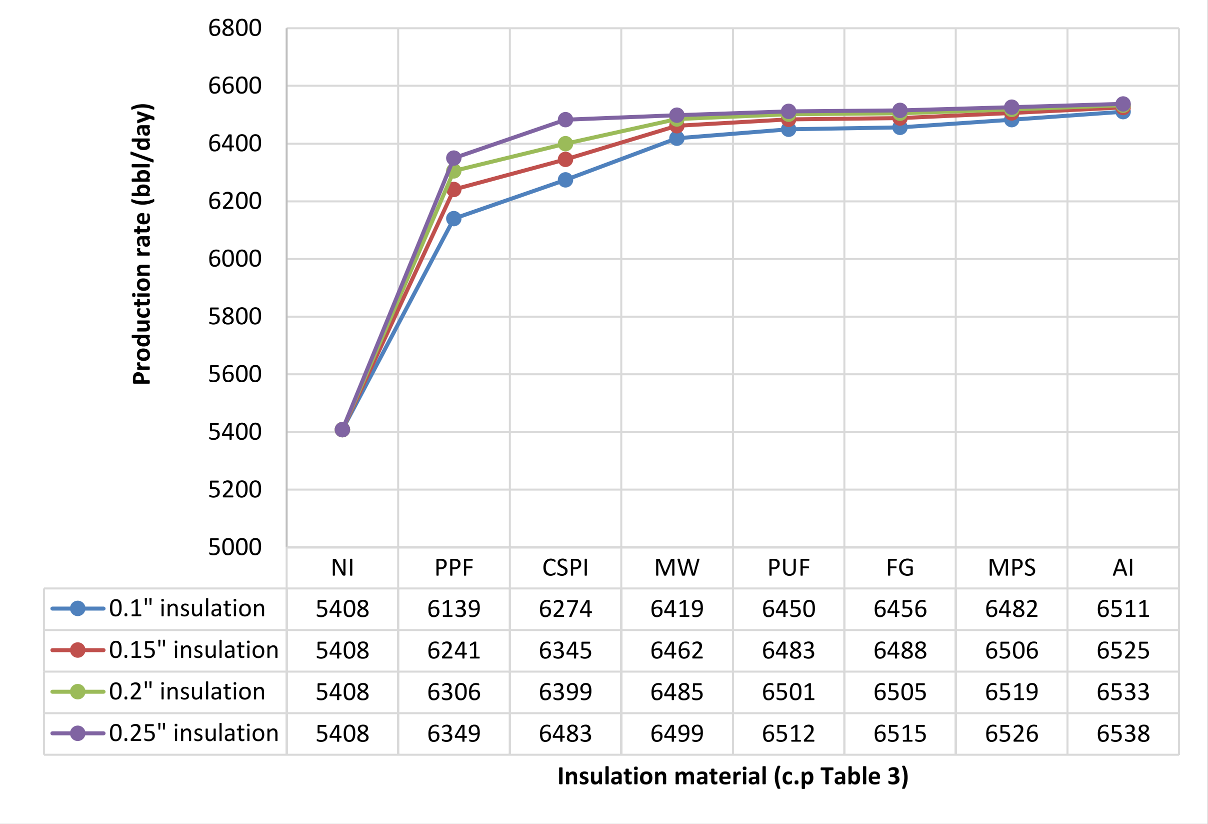


	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1 inch	89.4	33.4	23.1	11.6	9.0	8.5	6.3	3.9
0.15 inch	89.4	25.6	16.8	8.0	6.2	5.8	4.2	2.6
0.2 inch	89.4	20.7	13.2	6.1	4.6	4.4	3.2	1.9
0.25 inch	89.4	17.2	10.7	4.9	3.7	3.5	2.5	1.5

Figure 22: Overall heat transfer of the well for internal insulation (26°API)

The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18). Figure 22 shows that the overall heat transfer decreases when the thermal conductivity of insulation is reduced from one material to another. For instance, polypropylene foam insulation has reduced the overall heat transfer by three times while mineral wool insulation has diminished it by eight times. Aerogel results always the lowest overall heat transfer coefficients due to having the lowest thermal conductivity among the materials used.

The results of overall heat transfer coefficients are implemented in the PIPESIM software for the simulation. The simulation was run for all the insulation material with different insulation thickness. The first output that will be analyzed from the simulation is the production rate of the well.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	5408	6139	6274	6419	6450	6456	6482	6511
0.15" insulation	5408	6241	6345	6462	6483	6488	6506	6525
0.2" insulation	5408	6306	6399	6485	6501	6505	6519	6533
0.25" insulation	5408	6349	6483	6499	6512	6515	6526	6538

Figure 23: Production rates of the well for internal insulation (26°API)

In case of 0.1” inside insulation, the production rate has increased to a minimum value of 6139 bbl/day for polypropylene foam and to a maximum value of 6511 bbl/day for aerogel. Thus, the production gain percentage is between 13.5% and 20.4%.

Increasing the insulation thickness to 0.15” has increased the production rate to a minimum of 6241 bbl/day and a maximum of 6525 bbl/day. Thus, 0.15” thickness leads to an increasing percentage varying between 15.4% and 20.7%.

Furthermore, the insulation thickness is augmented to 0.2”, which results in an increase in production rate to 6306 bbl/day in case of polypropylene foam and 6533 bbl/day in case of aerogel. Therefore, the percentage of increase in production is between 16.6% and 20.8%.

The highest production rates for the different insulation materials were obtained in case of using 0.25” internal insulation. The production rate has reached a minimum of 6349 bbl/day in case of polypropylene foam and a maximum of 6538 bbl/day in case of aerogel. The increase percentage obtained in this case was between 17.4% and 20.9%. Therefore, increasing the insulation thickness allows a higher increase in production rate.

In comparison to the external insulation, internal insulation has shown slightly better production results. For instance, the propylene foam has led to a production rate of 6093 bbl/day in case of 0.1” outside insulation and 6139 bbl/day in case of inside insulation.

The inside insulation of the tubing has also affected the temperature profile of the well. The temperature profile of the well in case of 0.1” is shown for different insulation materials in Figure 24.

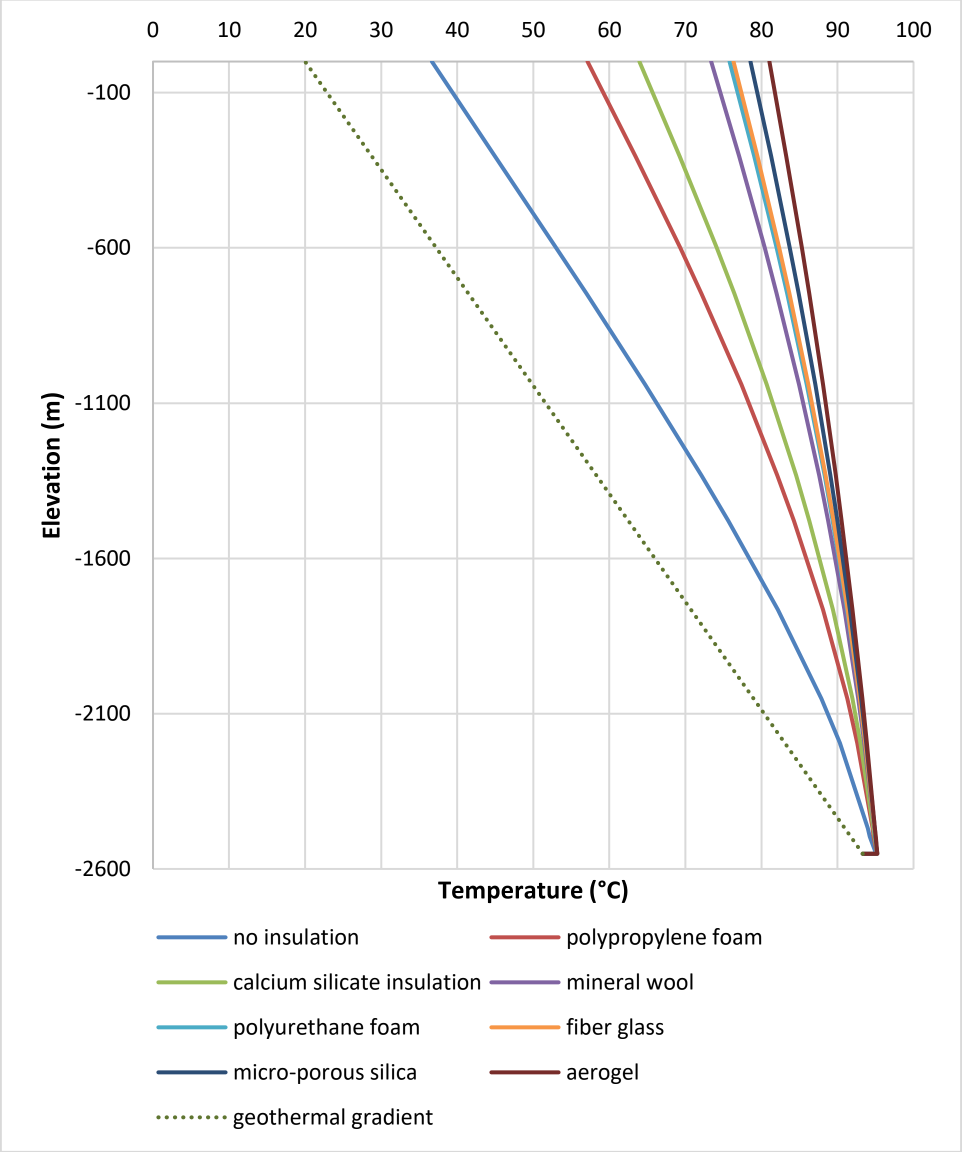


Figure 24: Temperature profiles of the well for 0.1" internal insulation (26°API)

Figure 24 shows different temperature profiles of several insulation materials resulted from the PIPESIM simulation. Without insulation, the temperature has decreased significantly from 95°C to 36°C that can cause the formation of precipitations, especially in the surface equipment. Internal insulation of the tubing has decreased the temperature losses in the well. The temperature has dropped from 95°C to 57°C, which was the maximum temperature loss obtained in case of polypropylene foam. As the thermal conductivity decreases from one insulation material to another, the temperatures loss decreases as well.

The lowest temperature losses were obtained in case of aerogel where the temperature has decreased from 95°C to 81°C. Therefore, adding inside insulation with 0.1” thickness can preserve up 45°C and keeps the fluid at a temperature higher than 55°C.

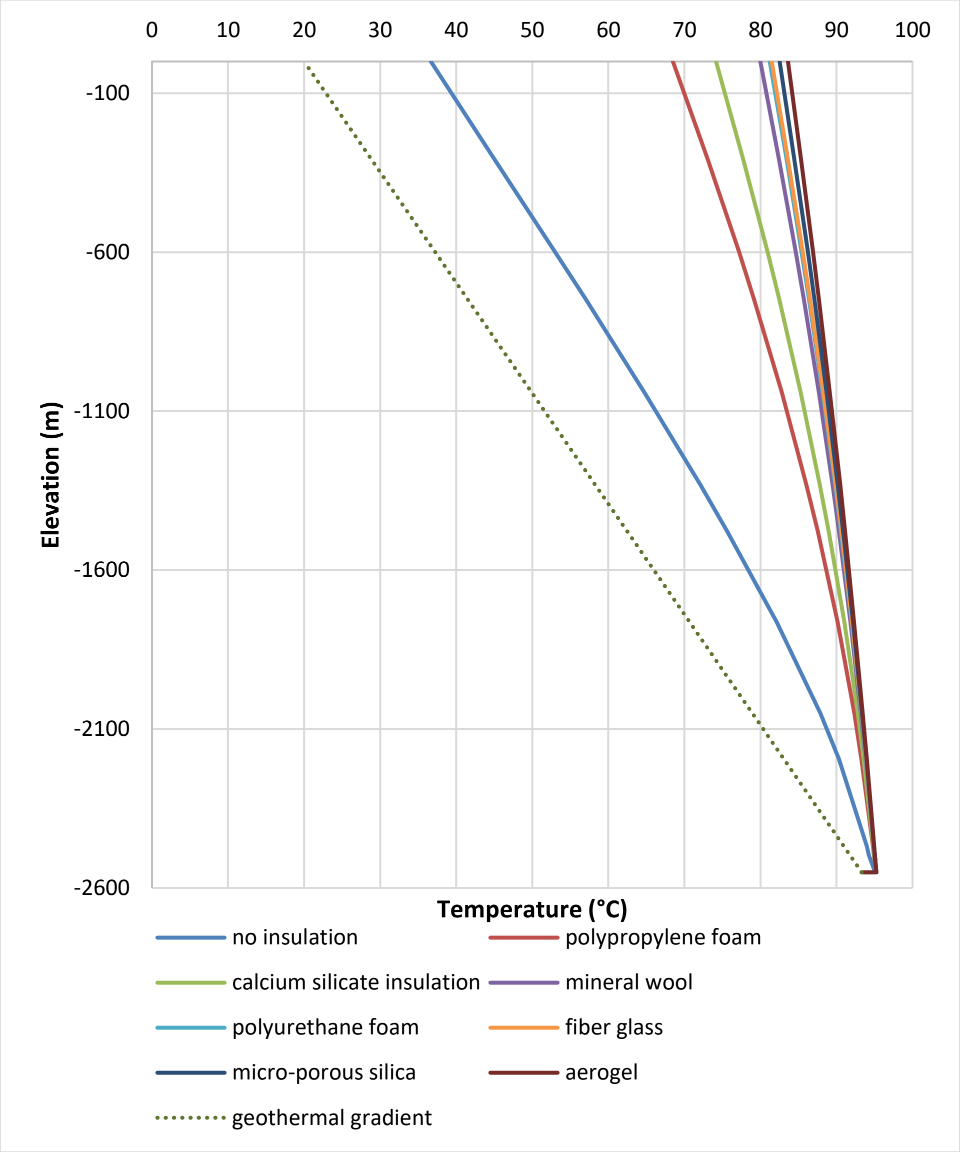


Figure 25: Temperature profiles of the well for internal insulation (26°API)

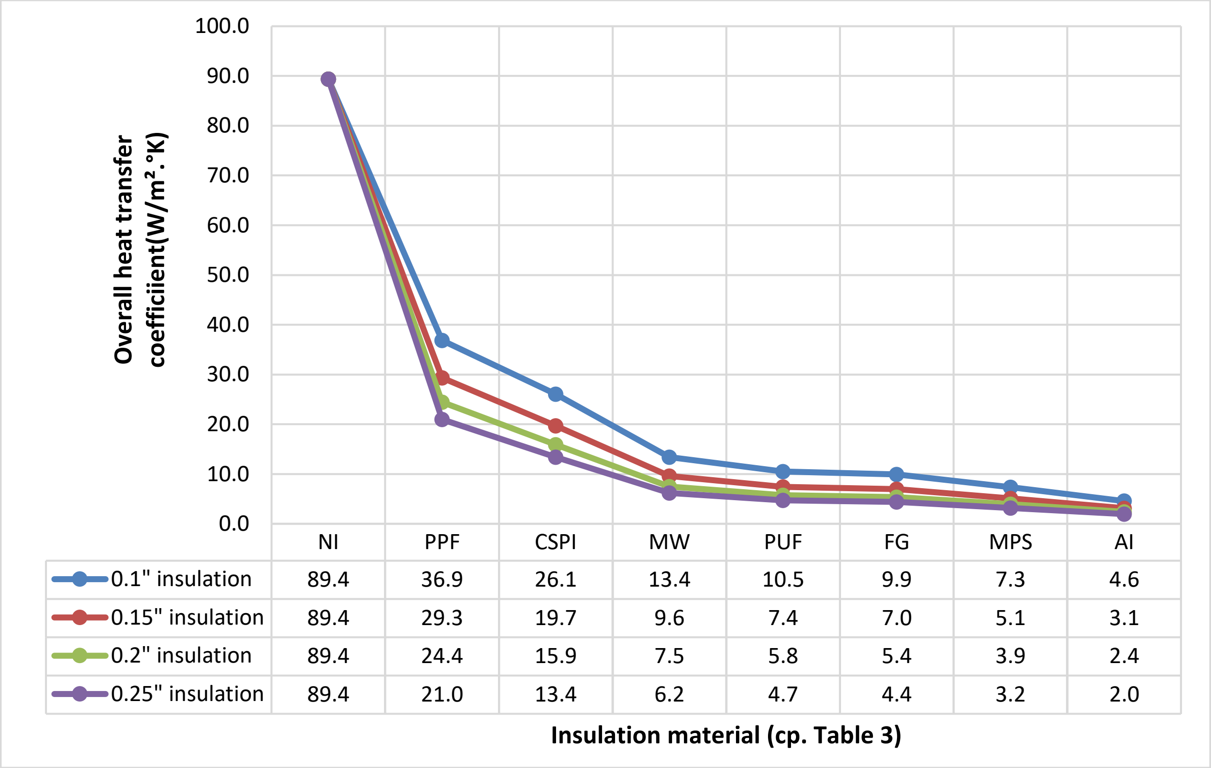
Increasing the insulation thickness to 0.25” has reduced the temperature losses, which is illustrated in Figure 25. The output temperature has risen from 57°C to 68°C, which results in 11°C heat preservation. The temperature losses have decreased by 10°C in case of calcium silicate insulation. The temperature profiles for the rest of insulation materials were very close, and the difference was small. The resulted output temperature was above 80°C for mineral wool, polyurethane foam, fiberglass, micro-porous silica, and aerogel. The minimum temperature losses were obtained in case of aerogel where the temperature has decreased from 95°C to 83.6°C. Therefore, internal insulation of the tubing has preserved a minimum of 21°C and a maximum of 47°C for a thickness varying between 0.1” and 0.25”.

The temperature profiles were very close when using the same insulation thickness for inside and outside insulation. For example, based on the case of polypropylene foam, the temperature has decreased from 95°C to 65.5°C in case of external insulation and from 95°C to 68.5°C in case of internal insulation for 0.25” thickness.

Therefore, the inside insulation is a better option than the outside for medium oil well in case of using a thickness between 0.1” and 0.25” due to the fact of having higher productivity gains and lower temperature losses.

4.2.2 External insulation

In this part, the insulation is simulated outside the production tubing for thicknesses varying between 0.1” and 0.25”. First, the overall heat transfer of the well is calculated for each case in order to implement it in the software as an input. The results of the calculation of the overall heat transfer are shown in Figure 26. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).



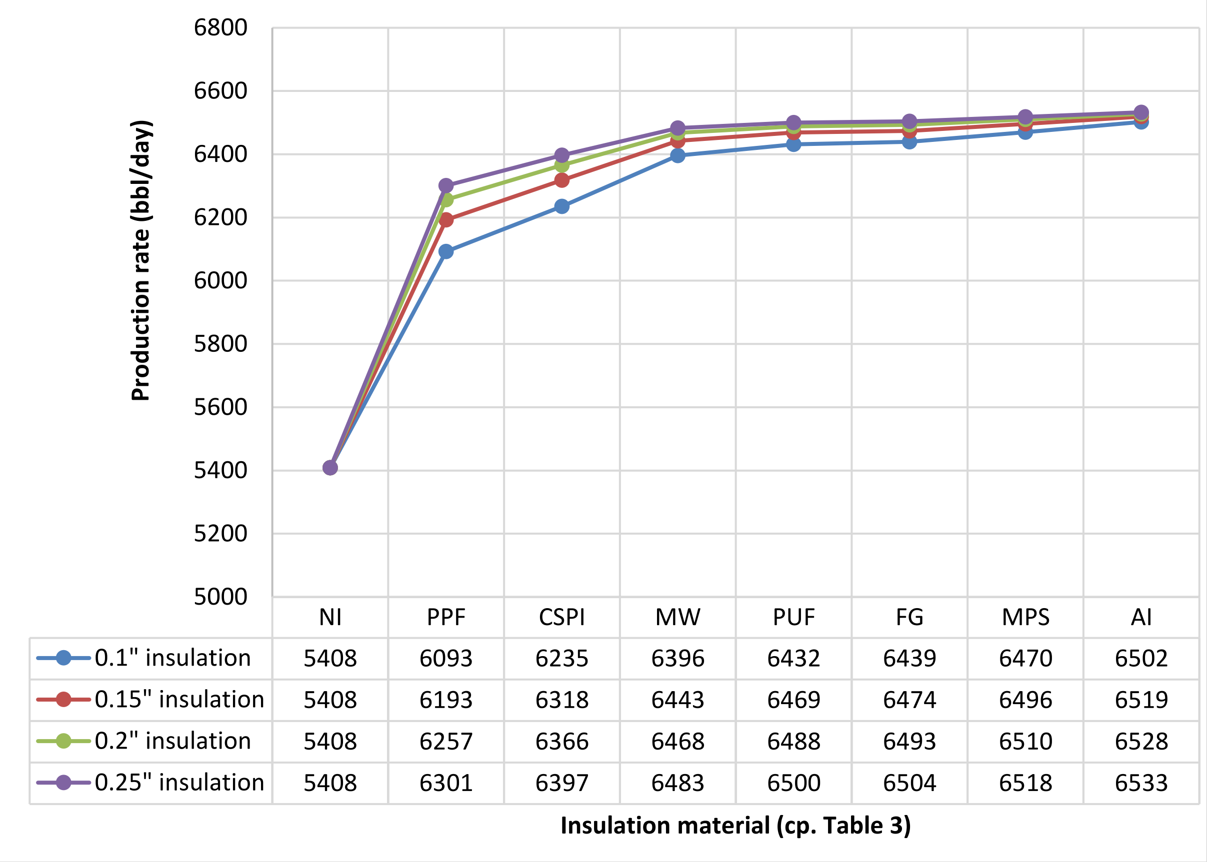
	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	89.4	36.9	26.1	13.4	10.5	9.9	7.3	4.6
0.15" insulation	89.4	29.3	19.7	9.6	7.4	7.0	5.1	3.1
0.2" insulation	89.4	24.4	15.9	7.5	5.8	5.4	3.9	2.4
0.25" insulation	89.4	21.0	13.4	6.2	4.7	4.4	3.2	2.0

Figure 26: Overall heat transfer of well for external insulation (26 °API)

Based on Figure 26, adding an insulation material has reduced the overall heat transfer by three times the magnitude compared to the no insulation case where the value was 89.3 W/m²K.

In fact, the magnitude of reduction has varied depending on the thermal conductivity of insulation material. The decrease of thermal conductivity between the insulators reduces the overall heat transfer of the well. The variation of insulation thickness has also affected the overall heat transfer results.

Figure 26 illustrates also that increasing the insulation thickness has reduced the overall heat transfer of the well. For instance, the overall heat transfer of polypropylene foam has been reduced from 36.8 to 21 W/m²K when increasing the thickness from 0.1” to 0.25”. The results of overall heat transfer are used in PIPESIM to generate the output results such as production rate and temperature profile of the well.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	5408	6093	6235	6396	6432	6439	6470	6502
0.15" insulation	5408	6193	6318	6443	6469	6474	6496	6519
0.2" insulation	5408	6257	6366	6468	6488	6493	6510	6528
0.25" insulation	5408	6301	6397	6483	6500	6504	6518	6533

Figure 27: Production rate of the well for external insulation (26°API)

The external insulation had a significant impact on the production rate of the well as illustrated in Figure 27. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).

In no insulation case, the well has produced only 5408 bbl/day. However, the production rate has increased to 6093 bbl/day which was the lowest increase noticed in polypropylene foam. The production rate increase as the insulation material is changed due to the fact of decrease of overall heat transfer. The maximum increase in production was obtained in aerogel case where the production rate has reached 6502 bbl/day. To sum up, the 0.1” insulation results have shown that the increasing percentage of production was between 12% and 20.2%.

When the insulation thickness was increased to 0.15”, the production rate has improved as well. The results have illustrated that the production has risen to a minimum of 6193bbl/day and a maximum of 6519bbl/day. The increase was obtained for all the insulation materials but with different amounts. For instance, an increase of 100 bbl/day was achieved in case of polypropylene foam while the aerogel case result has shown a rise of 17bbl/day. Thus, the percentage of gain has varied between 14.5% and 20.5%.

Increasing the insulation thickness to 0.2” has increased as well the production rate of the well. The liquid rate has reached a minimum of 6257 bbl/day in polypropylene foam case and a maximum of 65238 bbl/day in aerogel case. Thus, the increase percentage in case of 0.2" outside insulation was between 15.7% and 20.7%.

The best production results were obtained in case of 0.25" insulation. In fact, the minimum liquid flowrate was 6301 bbl/day, which has increased by around 900 bbl/day compared to no insulation case. The maximum production rate was 6533 bbl/day in aerogel case. Thus, the production gain obtained in this case has varied between 16.5% and 20.8%.

To sum up, the outside insulation of the well producing medium oil (26°API) for a thickness between 0.1" and 0.25" has guaranteed an increasing percentage varying between 12% and 20.8% depending on the insulation material used.

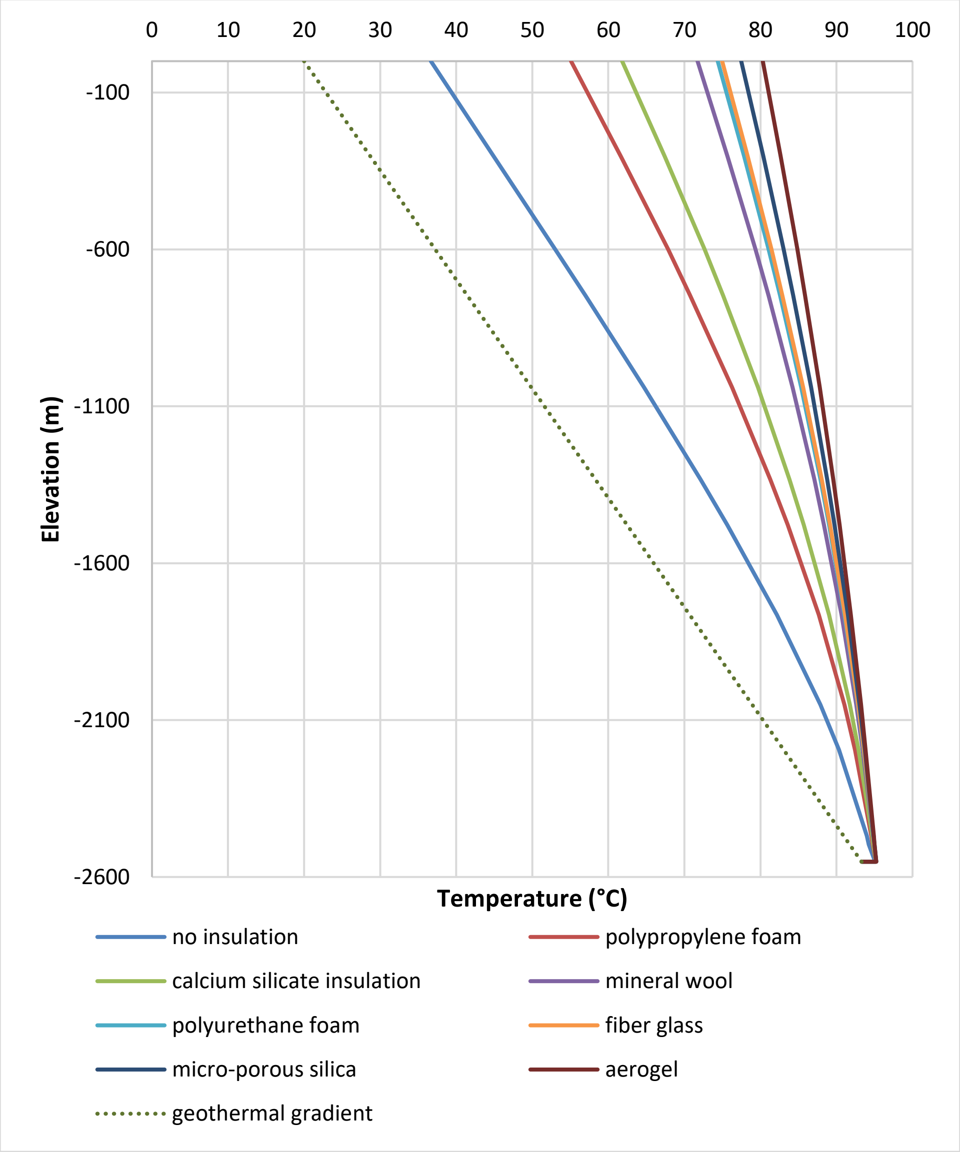


Figure 28: Temperature profile of the well for 0.1" external insulation (26°API)

Figure 28 shows temperature profiles plots resulting from the outside insulation of tubing using 0.1" thickness. In no insulation case, the temperature has decreased significantly from 93°C to 36°C, which may cause the formation of the precipitations due to this high drop in temperature.

Adding the insulation decreased the temperature losses in the well, and the results has differed from one insulation material to another. The lowest gain was obtained in case of polypropylene foam where the temperature has decreased from 95°C to 55°C. Therefore, the heat was preserved at 19°C in the presence of insulation material with the highest thermal conductivity. The temperature losses decrease as shown in Figure 28 as the thermal conductivity of the insulator decreases. Polyurethane foam and fiberglass had nearly the similar temperature profiles, as the temperature difference at the top was only 0.58°C. The maximum decline in temperature losses resulted from using aerogel insulation. The output temperature was 80°C, which means that the temperature has decreased only by 13°C from the reservoir to the wellhead. Therefore, the preservation of heat in comparison to no insulation case is between 19°C and 44°C as illustrated in Figure 28.

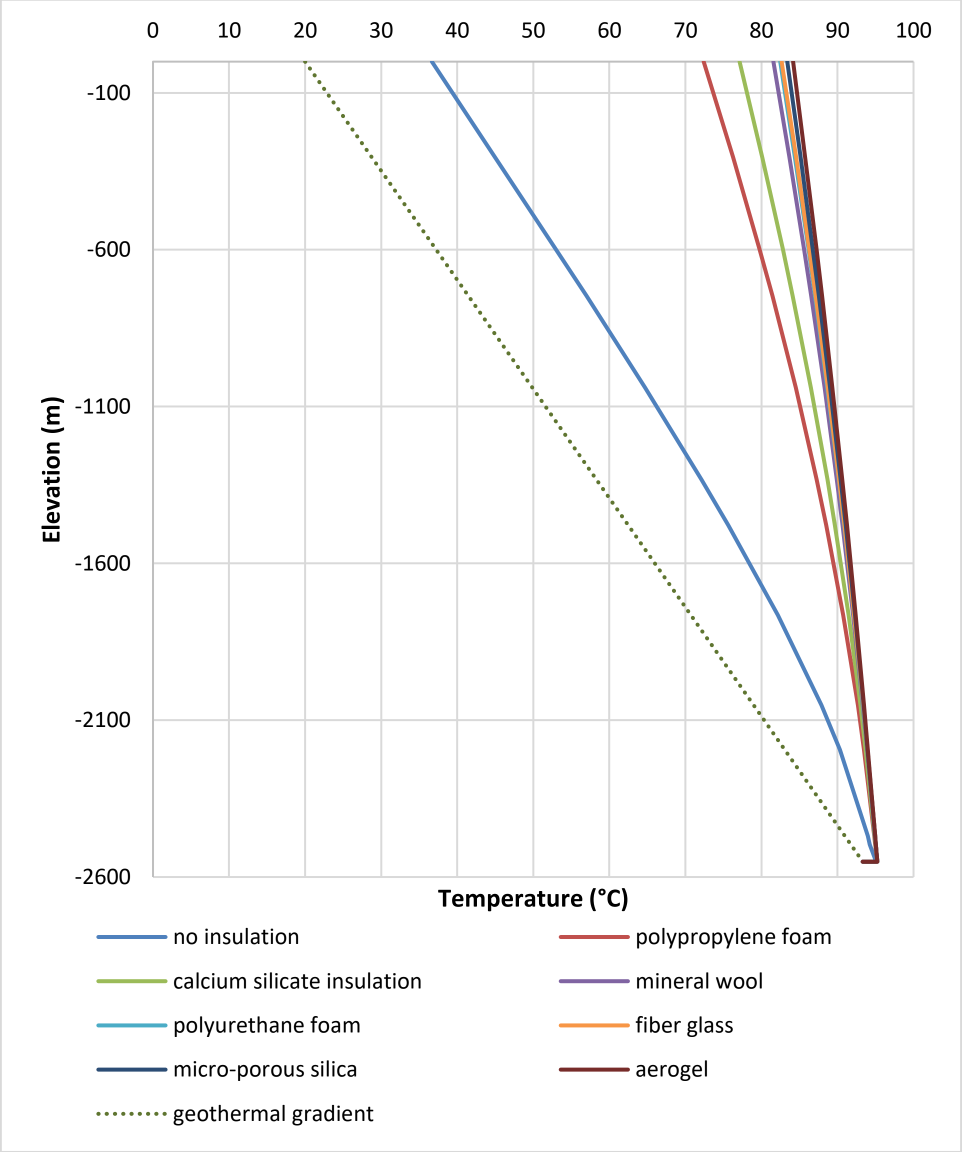


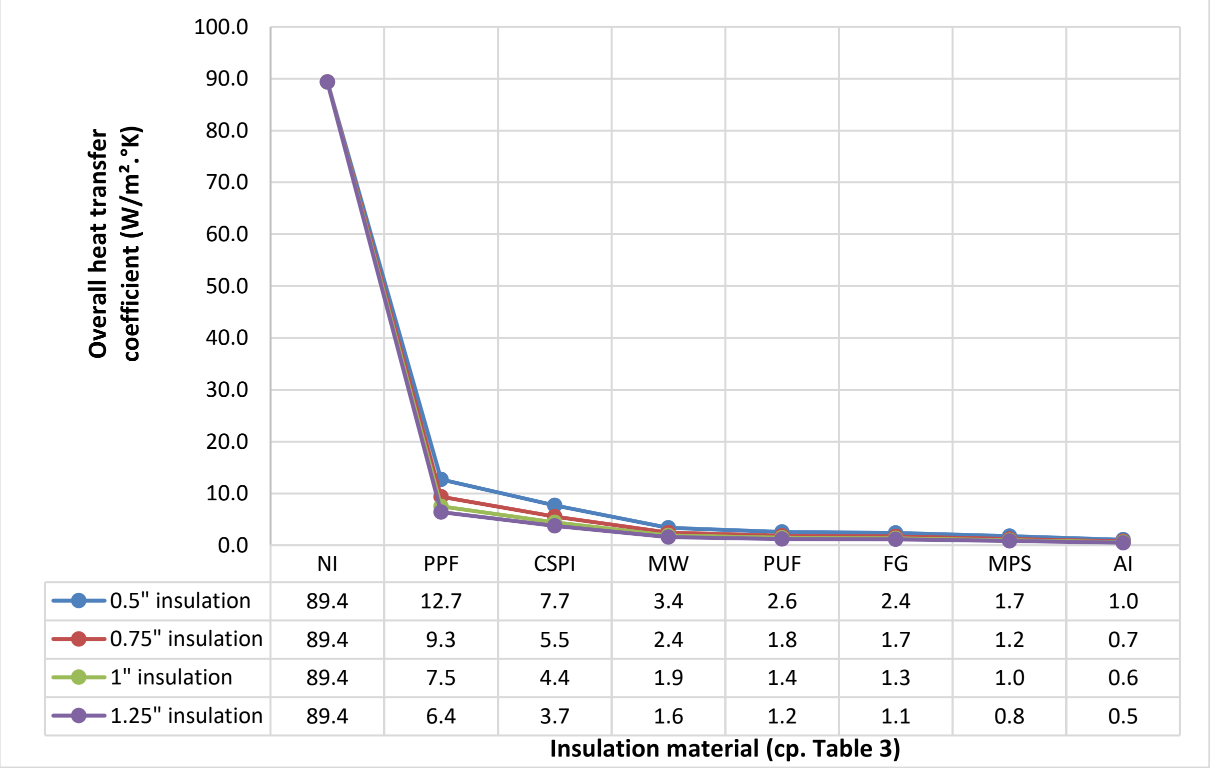
Figure 29: Temperature profiles for 0.25" external insulation (26°API)

Figure 29 shows the temperature profiles in case of using 0.25” outside insulation. According to the graph, increasing the isolation thickness has decreased more the temperature losses in the well. For instance, the temperature losses of the well has decreased in case of polypropylene foam and calcium silicate by 10°C when the insulation thickness has increased from 0.1” to 0.25”. The output temperature has increased from 71°C to 78.6°C in mineral wool case. The polyurethane foam and fiberglass had a very close temperature profile where the output temperature was around 80°C. In case of micro-porous silica insulation, the temperature losses have decreased by 4°C and the output temperature was around 81°C. The maximum preservation of the temperature was achieved in case of aerogel, where the temperature has decreased from 95°C to only 83°C. Increasing the thickness has decreased the temperature losses by only 3°C in case of aerogel.

4.2.3 Extended external insulation

The internal insulation of tubing cannot be applied for a thickness higher than 0.25” due to tubing size limitations. It can tremendously reduce the inside diameter of the tubing, which can cause well problems. Therefore, the insulation will be applied only outside the pipe in this case study.

Four different insulation thicknesses were used in this case, which are 0.5”, 0.75”, 1” and 1.25”. The first step is to calculate the overall heat transfer coefficients by using the model for external insulation of tubing. The coefficient is calculated for all insulation materials in each value of thickness. The generated results are plotted in Figure 30. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.5" insulation	89.4	12.7	7.7	3.4	2.6	2.4	1.7	1.0
0.75" insulation	89.4	9.3	5.5	2.4	1.8	1.7	1.2	0.7
1" insulation	89.4	7.5	4.4	1.9	1.4	1.3	1.0	0.6
1.25" insulation	89.4	6.4	3.7	1.6	1.2	1.1	0.8	0.5

Figure 30: Overall heat transfer of the well for extended external insulation (26°API)

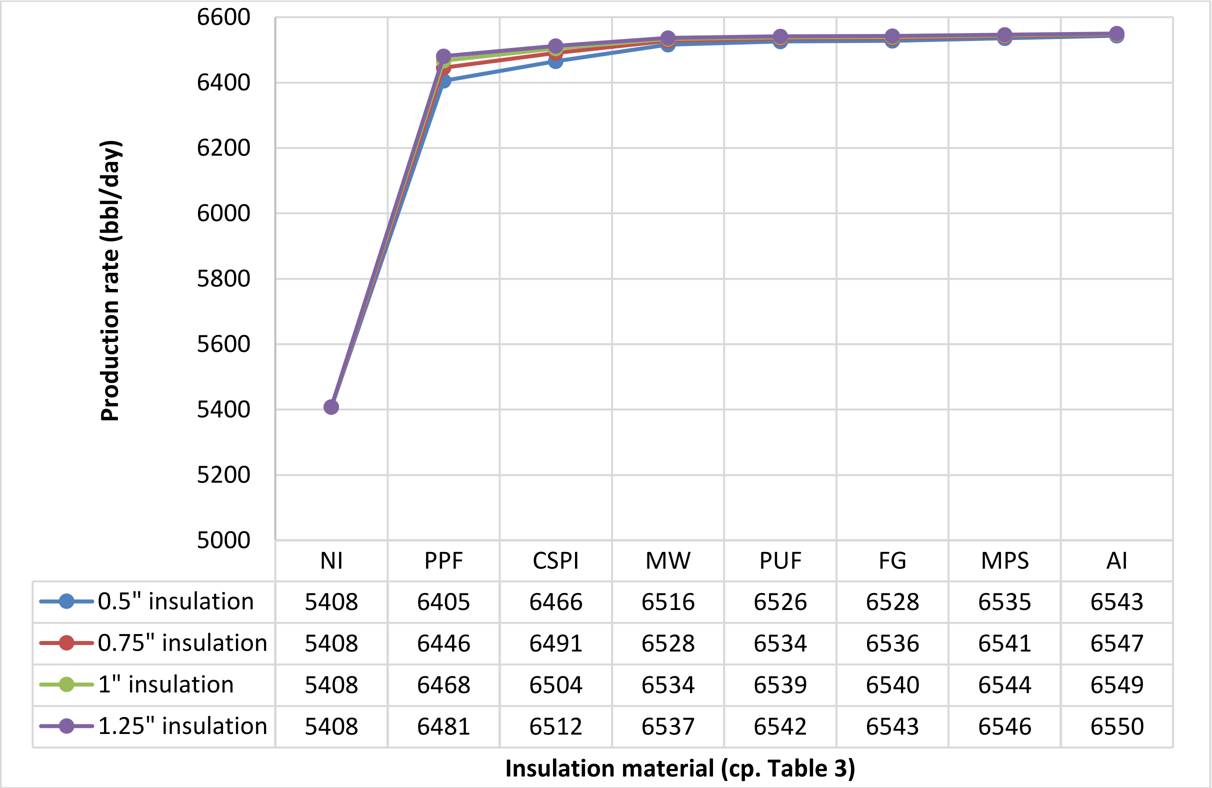
Figure 30 shows different results of overall heat transfer calculation for 0.5”, 0.75”, 1” and 1.25” outside insulation. For 0.5” thickness, the overall heat transfer has decreased from 89.3 W/m²K to at least 12.6 W/m²K, which is seven times less than the no insulation case. The values are decreasing in the graph due to the fact of decreasing thermal conductivity from one insulation material to another. The minimum value reached in case of 0.5” thickness is 1.04 W/m²K for aerogel insulation.

The increase of outside thickness to 0.75” has more decreased the overall heat transfer values. In fact, the decrease percentage was between 27% and 30% depending on the insulation material.

The insulation thickness is increased again to 1”, which has decreased the overall heat transfer in comparison to 0.75” insulation. For instance, the calcium silicate overall heat transfer coefficient has decreased from 5.5 W/m²K to 4.4 W/m²K. The decrease percentage of overall heat transfer from 0.75” to 1” outside insulation was between 20% and 22%.

The lowest values of heat transfer were obtained in case of 1.25” thickness. The overall heat transfer in this case has varied between 6.3 W/m²K and 0.4 W/m²K. In comparison to the no insulation cases, the heat transfer of the well has been reduced by a minimum of 15 times when using 1.25” insulation. Therefore, the higher the outside insulation thickness is, the lower the overall heat transfer of the well is.

The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.5" insulation	5408	6405	6466	6516	6526	6528	6535	6543
0.75" insulation	5408	6446	6491	6528	6534	6536	6541	6547
1" insulation	5408	6468	6504	6534	6539	6540	6544	6549
1.25" insulation	5408	6481	6512	6537	6542	6543	6546	6550

Figure 31: Production rate of the well for extended external insulation (26°API)

Adding a 0.5” outside insulation has guaranteed a minimum increase of 1000 bbl/day in case of the medium oil well. The maximum increase in production was 6543 bbl/day in case of 0.5” aerogel insulation. Therefore, the increase percentage, in this case, is between 18.4% and 20.9%.

Increasing the thickness to 0.75” has increased the production rate of the well but with different percentages. The minimum production rate was 6446 bbl/day in polypropylene foam case, and the maximum was 6547 bbl/day. Therefore, the increase percentage resulted from 0.75” is between 19.1% and 21 %.The amount of increase of production has varied from one insulation material to another. In fact, the highest increases were 40 bbl/day in case of polypropylene foam and 30 bbl/day in case calcium silicate, but the rest of insulation materials have shown a low increase in production that varied between 4 bbl/day and 10 bbl/day.

For an insulation thickness of 1”, the production rate has increased to a minimum value of 6468 bbl/day and a maximum value of 6549 bbl/day. Thus, the production gain for this thickness is between 19.5% and 21.09%. The polypropylene foam and calcium silicate were the most influenced in term of production rate as it increased by 22 bbl/day and 13 bbl/day respectively. However, the production rate of the rest of insulation materials has been improved only by values between 2 bbl/day and 6 bbl/day.

The best production rate results were obtained in case of 1.25” outside insulation. The minimum increase was from 5408 bbl/day in case of no insulation to 6481 bbl/day in case of polypropylene foam insulation. The production rate of the well has increased from one insulation type to another. The values were close especially for the cases of mineral wool (6537 bbl/day), polyurethane foam (6542 bbl/day), fiberglass (6543 bbl/day), micro-porous silica (6546 bbl/day) and aerogel (6550 bbl/day). Therefore, the installation of 1.25” insulation outside the tubing has provided a production gain between 19.8% and 21.1%.

To sum up, increasing the insulation thickness has increased the production rate but with different percentages depending on insulation material.

The next output result analyzed from PIPESIM simulation is the temperature profile of the well, which was generated for different insulation materials with different thicknesses.

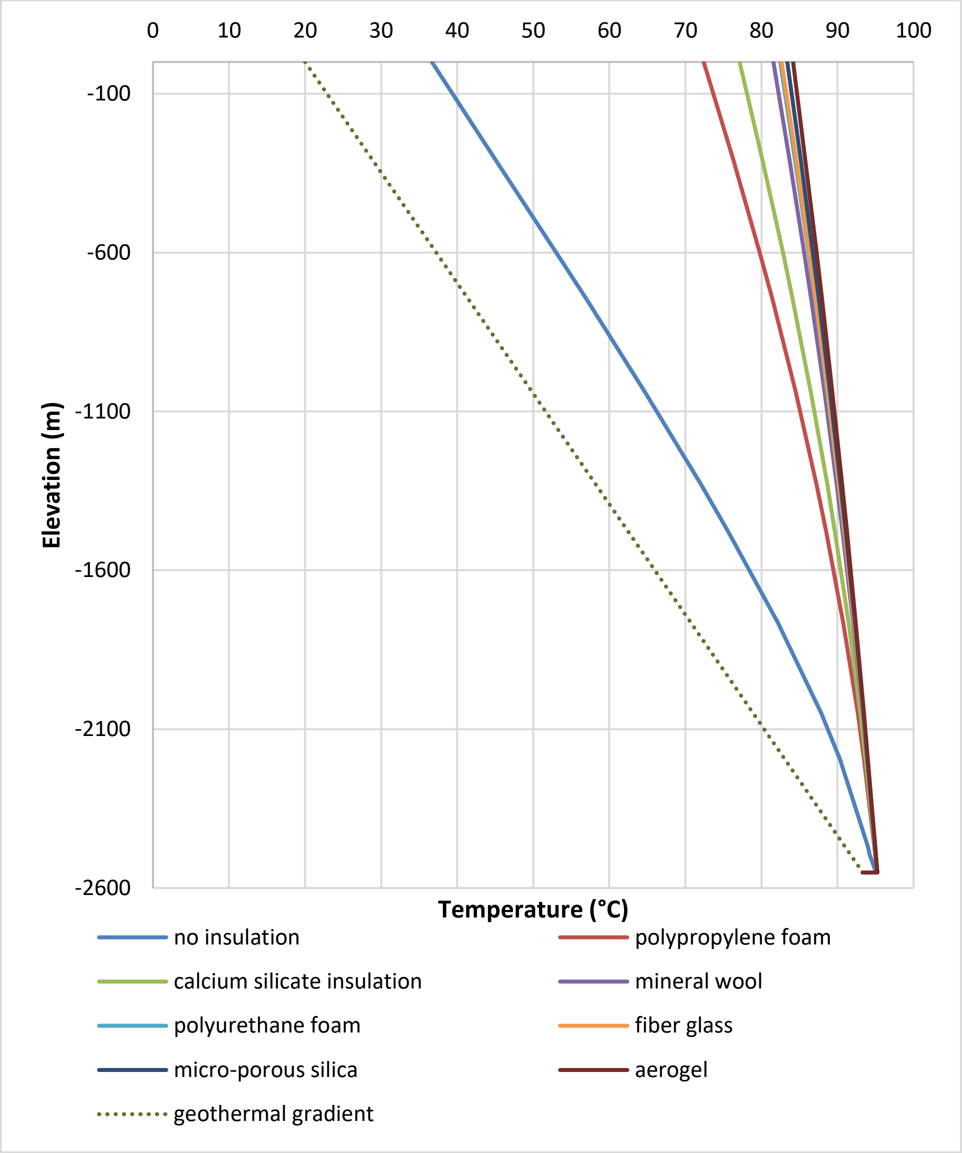


Figure 32: Temperature profile of well of 0.5” external insulation (26°API)

The plots of the temperature profile of the well for 0.5” insulation thickness is shown in Figure 32. The temperature losses have decreased significantly in the presence of insulation material. The output temperature has increased from 36°C to a minimum of 72°C in case of polypropylene foam, and the drop has decreased from 59°C to 23°C. In case of calcium silicate, the temperature losses have been reduced to 18°C, and the output temperature was 77°C. The highest decrease in temperature losses was in case of aerogel insulation with a value of 11°C.

Therefore, the external insulation of tubing had ensured an output temperature between 72°C and 84°C as illustrated in Figure 32.

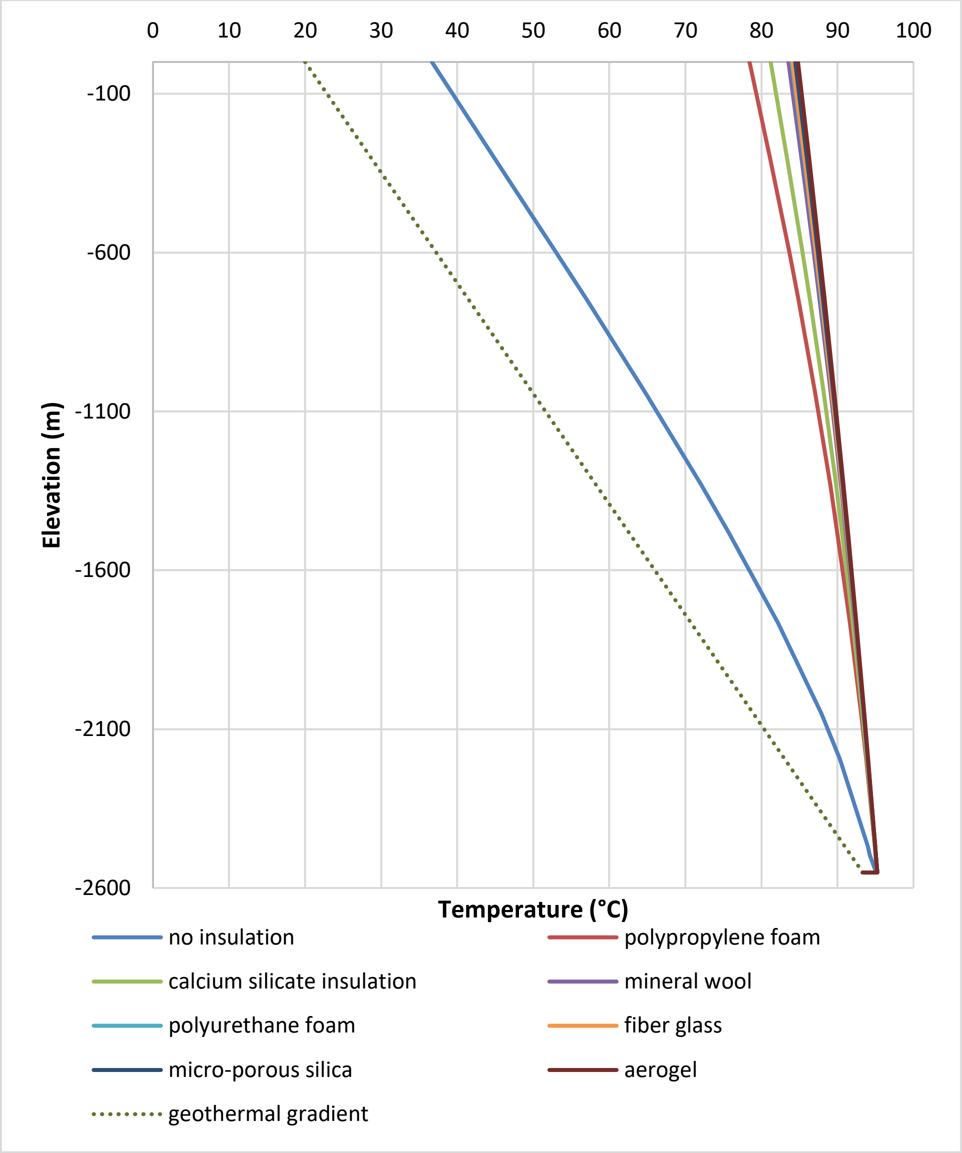


Figure 33: Temperature profile of the well for 1.25” external insulation (26°API)

The temperature profile for 1.25” insulation is plotted in Figure 33. The temperature losses have decreased as the insulation thickness has increased. For instance, the losses have dropped from 23°C to 17°C in case of polypropylene foam and from 18°C to 14°C in case of calcium silicate insulation. The rest of insulation material had very close temperature profiles as illustrated in Figure 33. The temperature losses for other cases were around 14°C. The minimum output temperature was 78°C in case of polypropylene foam.

The output temperature of each case has increased as the temperature a loss has decreased. The minimum output temperature was 78°C in case of polypropylene foam. The maximum output temperature was 84°C obtained for five different insulators, which are the mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel.

Therefore, increasing the insulation thickness to its maximum value has produced close temperature profiles and minimized the difference of output temperatures between the insulation materials.

4.3 Heavy oil simulation

In this section, a heavy oil well will be simulated in PIPESIM to see the impact of insulating the tubing on the output results. For this case, the insulation materials used for the simulation are the same ones used in the previous sections. The insulation thickness will be varied between 0.1” and 1.25” for external insulation and between 0.1” and 0.25” for internal insulation. The geometrical parameters and the fluid properties of the simulation are shown in the Table 11

Table 11: Stock tank properties of the heavy oil well

Stock tank properties	Value in PIPESIM model
Water cut (%)	10
GOR (Scf/STB)	500
API(°Api)	16°
Oil specific heat capacity (kJ/kgK)	1.88
Oil Thermal conductivity (W/mK)	0.48

Figure 34 shows the inflow performance and the vertical lift performance of the well. The well deliverability is 3524 bbl day at 3170 psi.

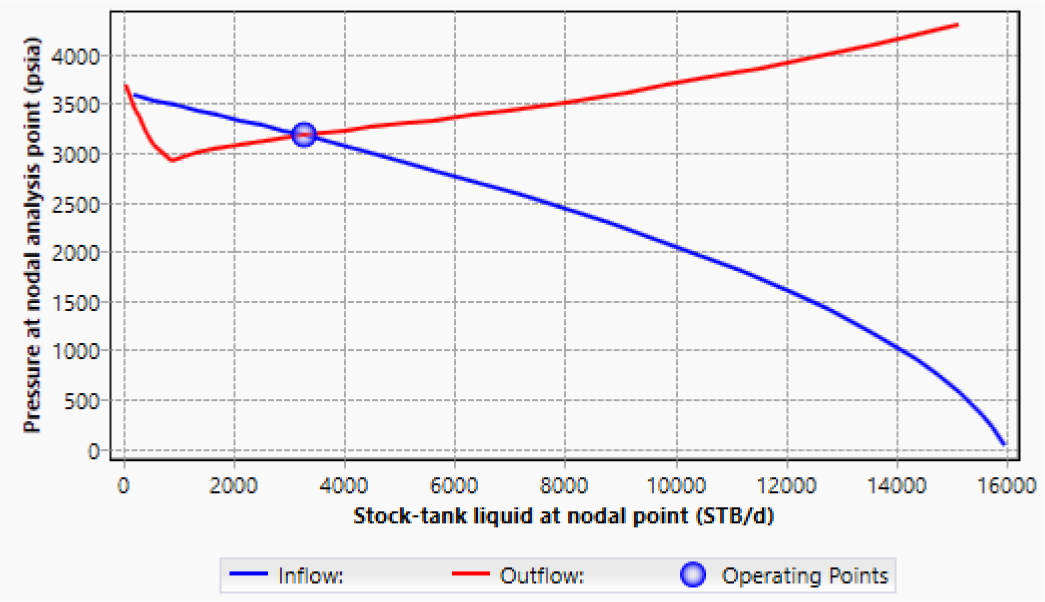
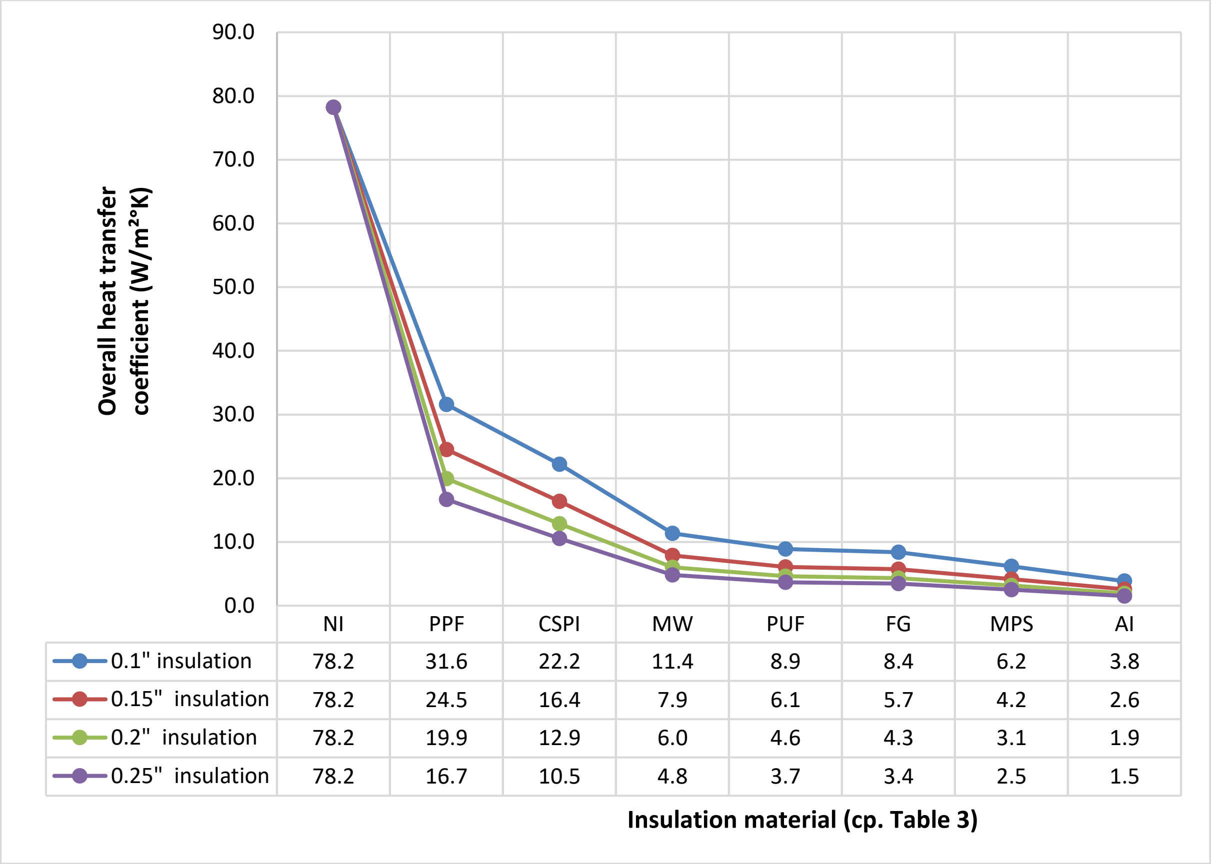


Figure 34: Inflow performance and vertical lift performance of the well (16°API)

4.3.1 Internal insulation

After analyzing the effect of external insulation in heavy oil well, the results are evaluated in case of using insulation inside the tubing by employing the same thickness values used in the previous section. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	78.2	31.6	22.2	11.4	8.9	8.4	6.2	3.8
0.15" insulation	78.2	24.5	16.4	7.9	6.1	5.7	4.2	2.6
0.2" insulation	78.2	19.9	12.9	6.0	4.6	4.3	3.1	1.9
0.25" insulation	78.2	16.7	10.5	4.8	3.7	3.4	2.5	1.5

Figure 35: Overall heat transfer of the well for internal insulation (16°API)

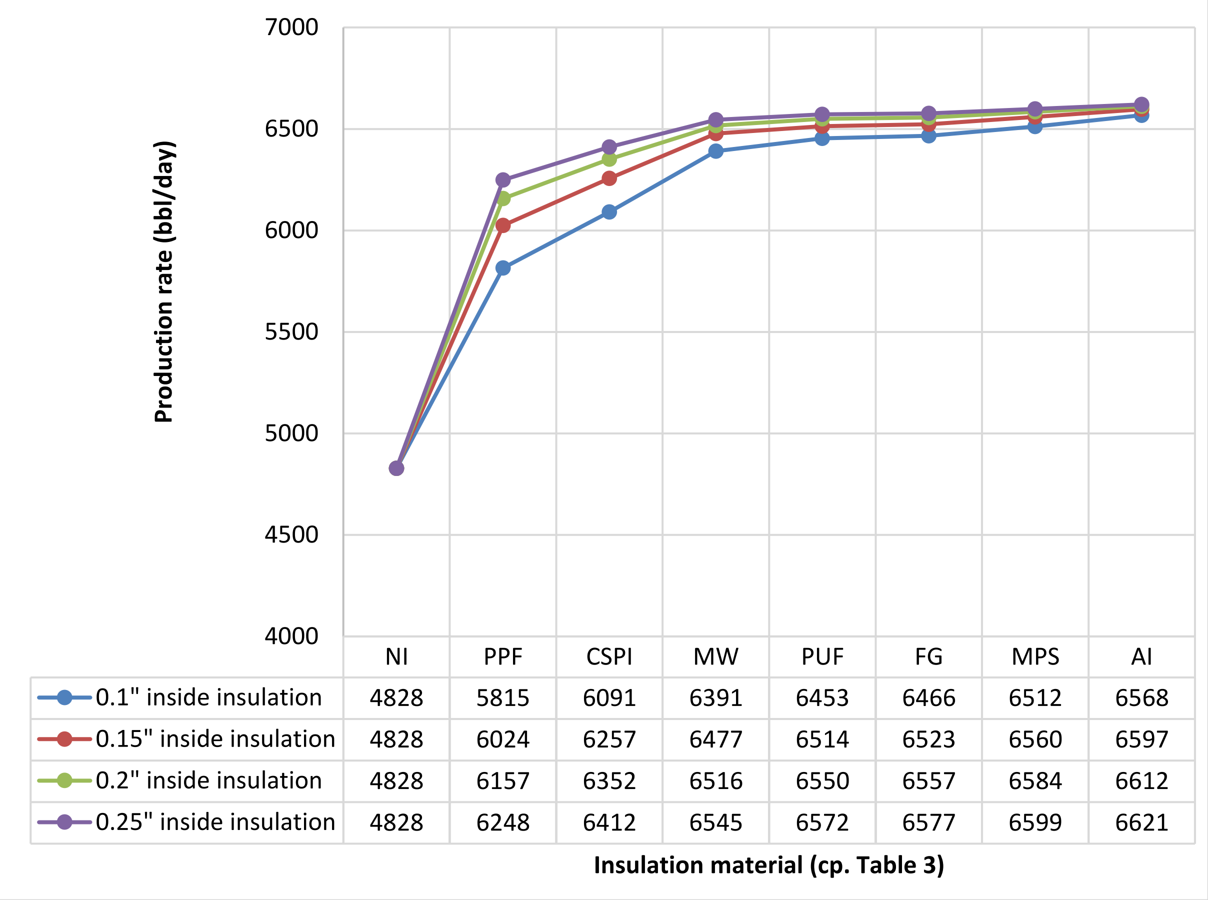
For 0.1” insulation, the overall heat transfer has decreased by at least 2.5 times from 78 W/m²K to 31.5 W/m²K. The decrease of thermal conductivity from one insulation material to another has decreased as well the overall heat transfer. The lowest overall heat transfer was 3.8 W/m²K in case of aerogel insulation.

Increasing the insulation thickness to 0.15” has resulted in the reduction of the overall heat transfer of the well for all the insulation materials as illustrated in Figure 35. The overall heat transfer of the well has decreased by at least three times in comparison to no insulation case. The results were ranging between 24.5 W/m²K in case of polypropylene foam and 2.5 W/m²K in case of aerogel.

In case of 0.2” insulation, the overall heat transfer has been reduced by a minimum of four times, which was obtained in case of polypropylene foam insulation. The increase of insulation thickness has decreased the heat losses in the well more than the previous case. The overall heat transfer has decreased from 78.2 W/m²K to a minimum of 19.9 W/m²K and a maximum of 1.9 W/m²K.

The lowest values of overall heat transfer were obtained in case of 0.25”, which is the highest thickness used in case of inside insulation. In fact, the values were less than 5 W/m²K for five different insulation materials, which are mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel. To sum up, adding 0.25” inside insulation has reduced the overall heat transfer to a minimum of 16.6 W/m²K and a maximum of 1.5 W/m²K.

It is noticeable that the internal insulation of the production tubing has resulted in lower values of overall heat transfer than the external insulation.



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" inside insulation	4828	5815	6091	6391	6453	6466	6512	6568
0.15" inside insulation	4828	6024	6257	6477	6514	6523	6560	6597
0.2" inside insulation	4828	6157	6352	6516	6550	6557	6584	6612
0.25" inside insulation	4828	6248	6412	6545	6572	6577	6599	6621

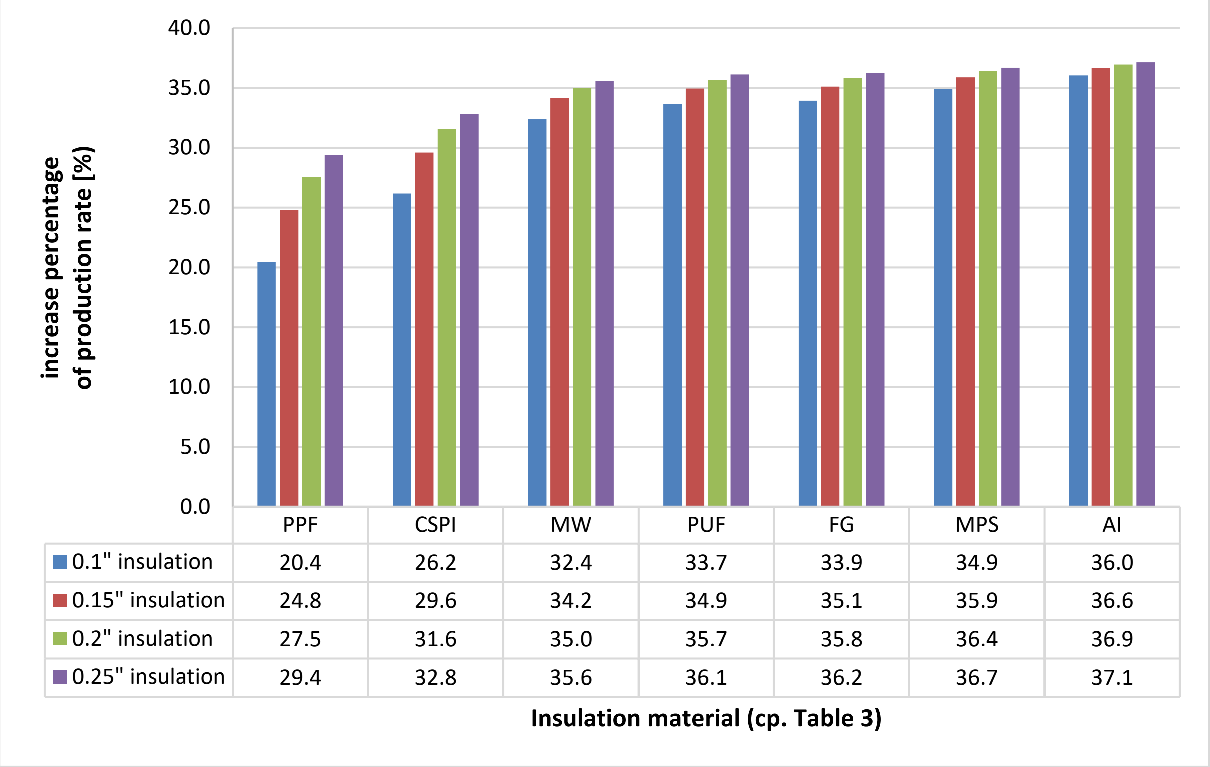
Figure 36: Production rates of the well for internal insulation (16°API)

The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18). Figure 36 shows four curves of different insulation thicknesses. For 0.1” inside insulation, the production rate has increased from 4828 bbl/day to a minimum of 5815 bbl/day and a maximum of 6568 bbl/day. Therefore, the production gain guaranteed from adding 0.1” inside insulation is between 20.4% and 36%.

For 0.15” inside insulation, the production has increased more and reached a minimum of 6024 bbl/day and a maximum of 6597 bbl/day. The production rate raised by a minimum of 20.4% and a maximum of 24.8 %.

In case of increasing the insulation thickness to 0.2”, the production rate of the well has increased to a minimum of 6157 bbl/day obtained when using propylene foam. The maximum production rate was 6597 bbl/day in case of aerogel insulation. Therefore, the use of 0.2” internal insulation in heavy oil has shown a production gain varying between 27.5% and 36.9%.

The highest production rate values were obtained in case of using 0.25” insulation thickness. In fact, the production rate increased to a minimum of 6248 bbl/day and a maximum of 6621 bbl/day. Thus, adding 0.25” inside insulation has guaranteed an increasing percentage of production between 29.4% and 37.1%.



	PPF	CSPI	MW	PUF	FG	MPS	AI
🟦 0.1" insulation	20.4	26.2	32.4	33.7	33.9	34.9	36.0
🟥 0.15" insulation	24.8	29.6	34.2	34.9	35.1	35.9	36.6
🟩 0.2" insulation	27.5	31.6	35.0	35.7	35.8	36.4	36.9
🟪 0.25" insulation	29.4	32.8	35.6	36.1	36.2	36.7	37.1

Figure 37: Increase percentage of production rate for internal insulation (16°API)

The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18). Figure 37 shows that the increase percentage of the production rate for different insulation materials. It is noticeable that increasing the insulation thickness has influenced especially the materials having the higher thermal conductivities. For instance, the gain percentage has increased by around 10% in case of polypropylene foam while it has risen only by 1% in case of aerogel from 0.1” to 0.25” internal insulation.

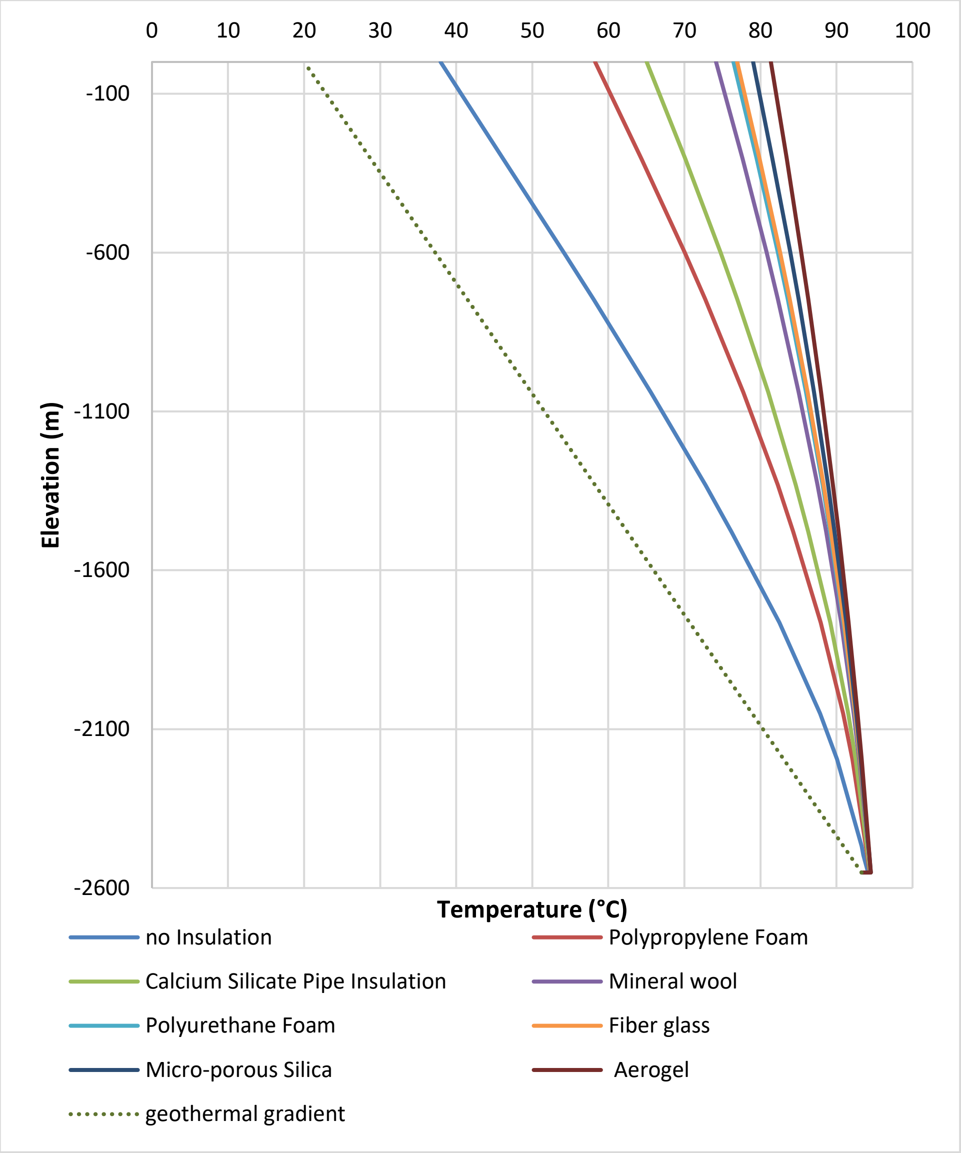


Figure 38: Temperature profile of the well for 0.1" internal insulation (16°API)

Figure 38 presents the temperature profile of the well in case of using different insulation materials and for an insulation thickness of 0.1”. The temperature has declined from 94°C to 37.9°C in no insulation case. Adding 0.1” inside insulation in the tubing has reduced the temperature losses along the wellbore with different magnitudes. For instance, the temperature has decreased from 94°C to 58°C in case of polypropylene foam while it has dropped to 65°C in case of calcium silicate insulation. The lowest temperature losses were obtained in case of aerogel where the temperature has decreased by only 13°C from 94°C to 81°C.

The output temperature of the well has increased as the temperature losses have decreased when adding the insulation. Based on the results from the plot, the output temperature has risen from 36°C in case of no insulation to a minimum of 58°C (polypropylene foam) and a maximum of 81°C (aerogel). Therefore, 0.1” inside insulation retains the fluid at a temperature higher than 58°C and can reduce the temperature losses up to 45°C.

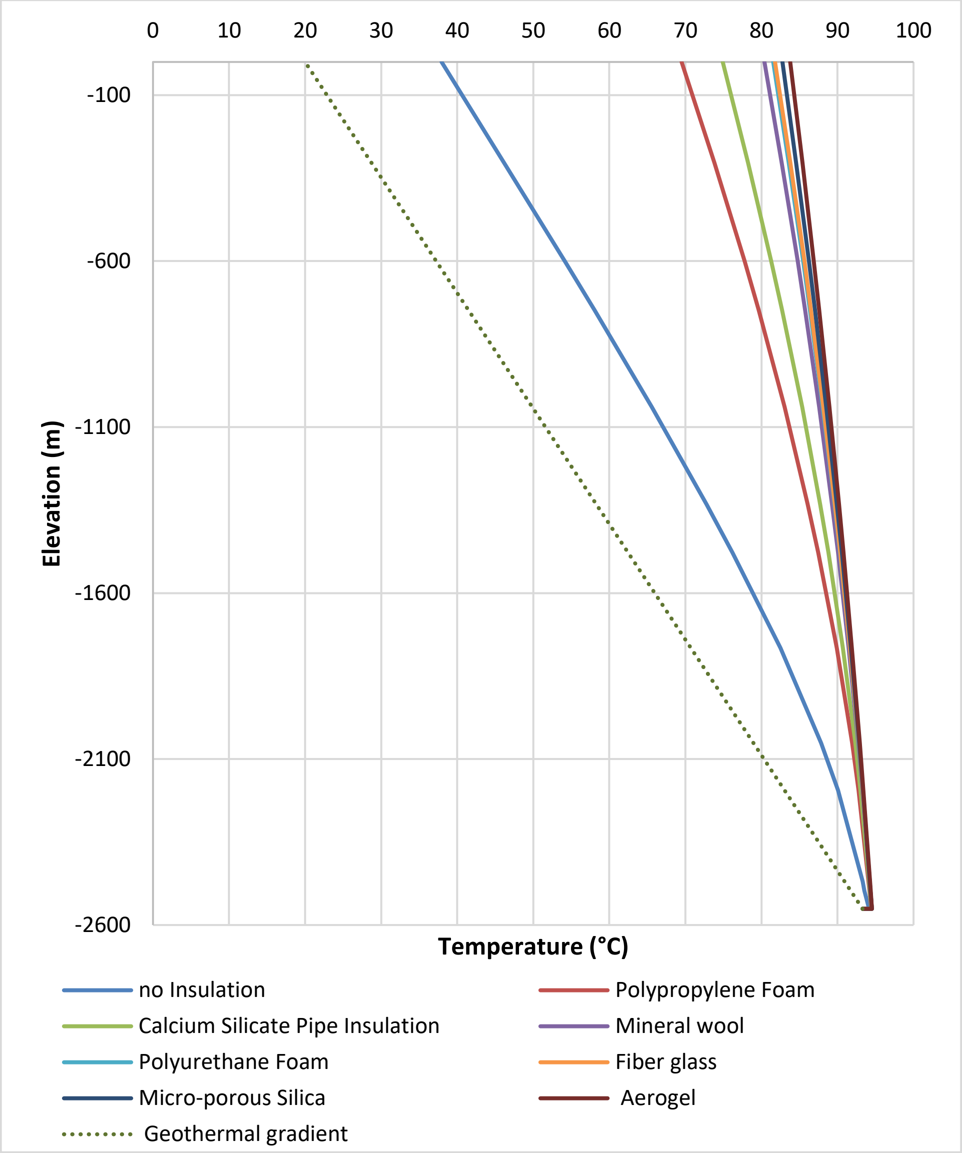


Figure 39: Temperature profile of the well for 0.25" internal insulation in (16 °API)

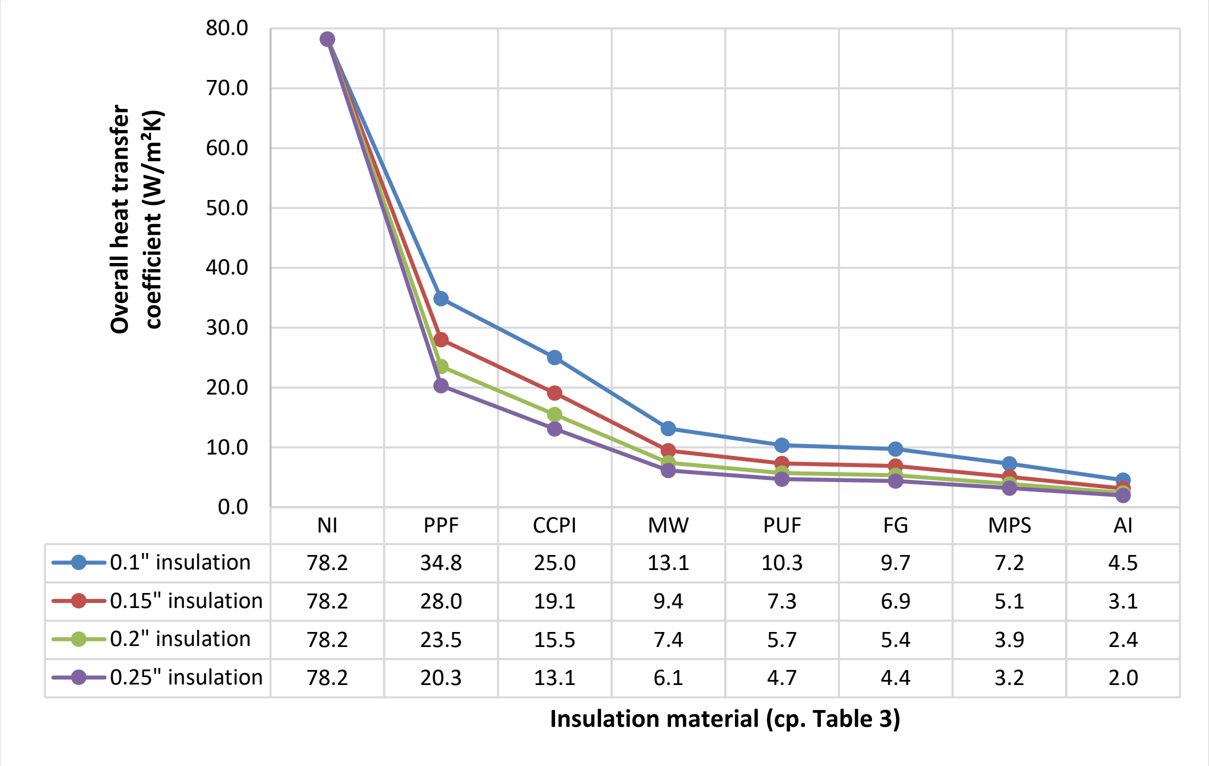
Figure 39 shows the different temperature profiles of the well for the 0.25” internal insulation of the tubing. The increase of insulation thickness has decreased the temperature losses along the wellbore with different percentage depending on the insulation material used. In fact, the temperature drop was reduced from 38°C to only 25°C when using the 0.25” polypropylene foam inside the tubing, which was the highest temperature gain obtained. The temperature losses decrease as the thermal conductivity decreases from one insulation materials to another. Five insulation materials had a very close temperature profile, which are mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel. The output temperature for these materials was above 80°C which results in a temperature drop less than 14°C.

To sum up, adding 0.25” insulation inside the tubing maintain the fluid temperature at a temperature higher than 69°C and decreases the temperature losses up to 11°C.

The internal insulation of tubing has decreased the temperature losses more than the external insulation especially when using the higher thermal conductivities insulators.

4.3.2 External insulation

In this case, the insulation will be applied outside the tubing for a thickness range between 0.1” and 0.25”. The overall heat transfer of the well is calculated at the first stage by using the Excel model for external insulation. The results of calculations are plotted in Figure 40 for different insulation thicknesses. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).



	NI	PPF	CCPI	MW	PUF	FG	MPS	AI
● 0.1" insulation	78.2	34.8	25.0	13.1	10.3	9.7	7.2	4.5
● 0.15" insulation	78.2	28.0	19.1	9.4	7.3	6.9	5.1	3.1
● 0.2" insulation	78.2	23.5	15.5	7.4	5.7	5.4	3.9	2.4
● 0.25" insulation	78.2	20.3	13.1	6.1	4.7	4.4	3.2	2.0

Figure 40: Overall heat transfer of the well for external insulation (16°API)

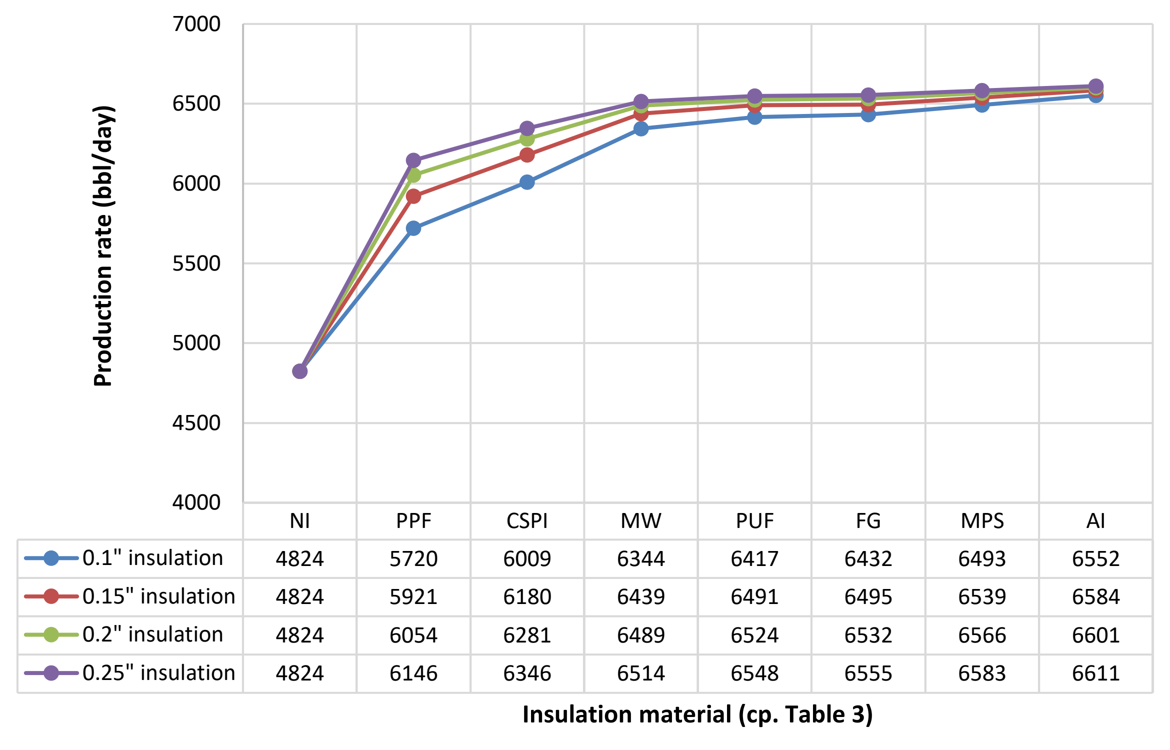
Figure 40 shows the effect of type of insulation material and insulation thickness on the overall heat transfer of the well. Without insulation, the heat transfer of the well has given a value of 78.2 W/m²K, which was the highest one obtained from the calculation. First, a 0.1” external insulation was applied to the tubing. The results show that the overall heat transfer has decreased by at least two times from 78.2 to 34.8 W/m²K in case of polypropylene foam. As the thermal conductivity decrease from one insulation material to another, the overall heat transfer of the well decreases as well until reaching a minimum value of 4.5 W/m²K in case of aerogel.

Figure 40 shows that the overall heat transfer has decreased again when the insulation thickness has been increased from 0.1” to 0.15”. In case of polypropylene foam, the overall heat transfer has decreased from 34.8 to 28 W/m²K. The lowest value was 3.1 W/m²K in case of aerogel.

In the next case, the insulation thickness was increased to 0.2”. The overall heat transfer of the well has decreased in comparison to lower thickness values. For instance, the overall heat transfer has decreased from 28 to 23.5 W/m²K in case of polypropylene foam. The minimum value was obtained in case of aerogel, which was 2.3 W/m²K.

The lowest values of overall heat transfer of the well were obtained in case of applying 0.25” outside insulation to the tubing. The minimum decrease was achieved in case of polypropylene foam where the overall heat transfer was 4 times less than the no insulation case (from 78.2 to 20.3 W/m²K). The overall heat transfer of the well was lower than 5 W/m²K for four different insulation materials, which were the polyurethane foam, fiberglass, micro-porous silica and aerogel. The minimum value of heat transfer for 1.25” insulation was 1.9 W/m²K in case of aerogel insulation.

The generated results of overall heat transfer coefficients are implemented on PIPESIM in order to run the simulation. For each run, the overall heat transfer of the well is modified depending on the type of insulation and the insulation thickness. The simulation will generate different results but the focus will be mainly on the production rate and the temperature profile of the well. The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18).



	NI	PPF	CSPI	MW	PUF	FG	MPS	AI
0.1" insulation	4824	5720	6009	6344	6417	6432	6493	6552
0.15" insulation	4824	5921	6180	6439	6491	6495	6539	6584
0.2" insulation	4824	6054	6281	6489	6524	6532	6566	6601
0.25" insulation	4824	6146	6346	6514	6548	6555	6583	6611

Figure 41: Production rate of the well for external insulation (16°API)

The production rate results of the well are plotted in Figure 41 for various insulation materials and thicknesses varying between 0.1” and 0.25”. In no insulation case, the production rate was 4828 bbl/day. The effect of adding an insulation material on the production rate is illustrated in Figure 41.

The lowest insulation thickness used in the simulation was 0.1”. The production rate has increased from 4828 bbl/day to a minimum value of 5720 bbl/day, which is around 892 bbl/day gain. It was higher than 6000 bbl/day for the rest of insulation materials. The production rate reached a maximum value of 6552 bbl/day in case of aerogel insulation. Thus, external insulation of tubing with 0.1” thickness provides a production gain between 18.6% and 34%.

Increasing the insulation thickness to 0.15” has increased the production rate more than the previous case. The minimum production rate obtained was 5921 bbl/day in case of polypropylene foam, and the maximum rate was 6584 bbl/day in case of aerogel insulation. Therefore, 0.15” outside insulation ensures a production increase by a minimum of 22.7% and a maximum of 36.5%. For 0.2” insulation, the production rate has increased to a minimum value of 6054 bbl/day and a maximum value of 6601 bbl/day. Therefore, the increase percentage rate is between 25.5% and 36.8%.

In case of 0.25” outside insulation, the production rate has reached its maximum value for all the insulation materials. The production rate has increased from 4824 bbl/day to a minimum of 6146 bbl/day in case of polypropylene foam and a maximum of 6611 bbl/day in case of aerogel. Therefore, using a 0.25” outside insulation for a heavy oil well ensures a production gain between 27.4% and 37%.

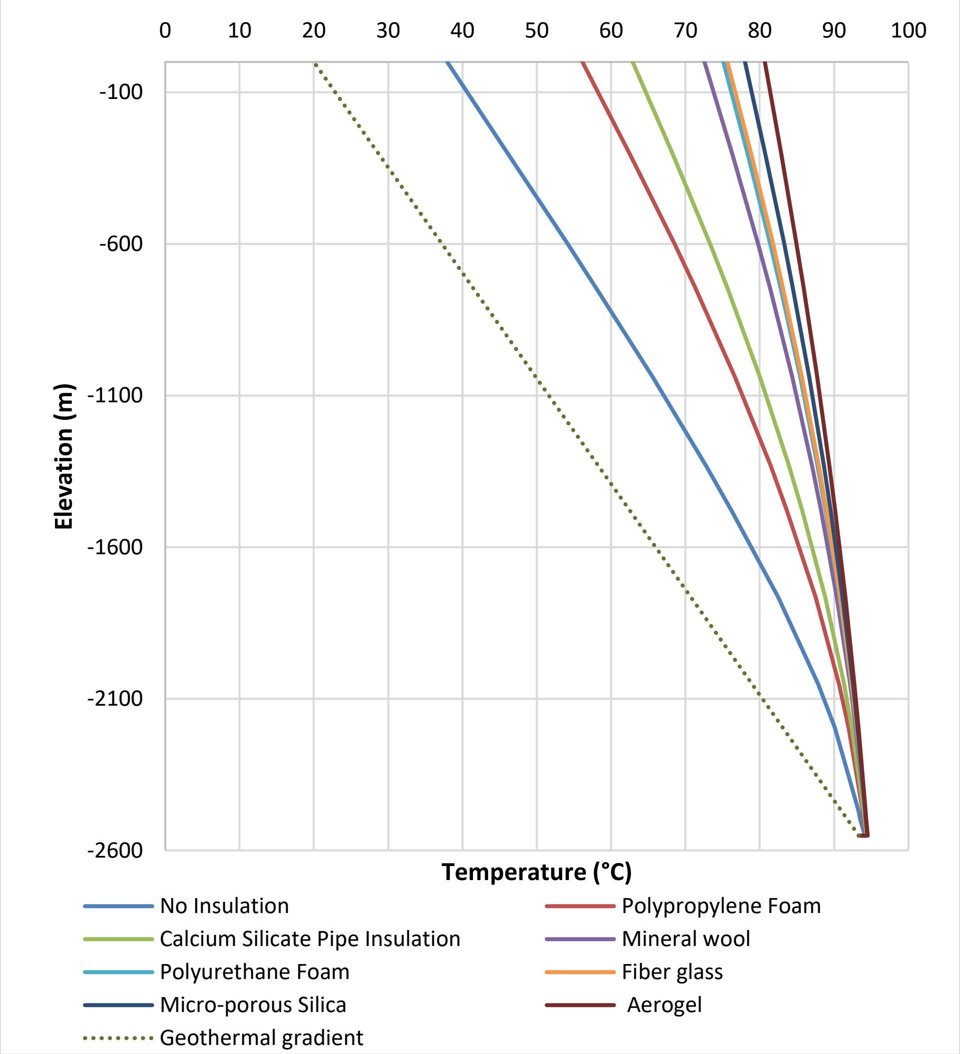


Figure 42: Temperature profile of the well for 0.1" external insulation (16°API)

In case of no insulation, the temperature has dropped tremendously along the wellbore from 94°C to 37.9°C. The high-temperature losses can cause the formation of precipitations in the well and can profoundly reduce its productivity.

Adding external insulation to the tubing of 0.1” has decreased the temperature losses in the well by a minimum of 20°C, which was illustrated in case of polypropylene foam. The temperature losses are minimized more and more as the thermal conductivity decreases from one insulation material to another. The lowest temperature drop was obtained in case of aerogel where the temperature has dropped by only 10°C from the reservoir to the wellhead. To sum up, the output temperature has risen to a minimum of 56°C in case of polypropylene foam and a maximum of 80°C in case of aerogel insulation.

Therefore, 0.1” external insulation in heavy oil well ensure a reduction in temperature losses by a minimum of 20°C and a maximum of 44°C.

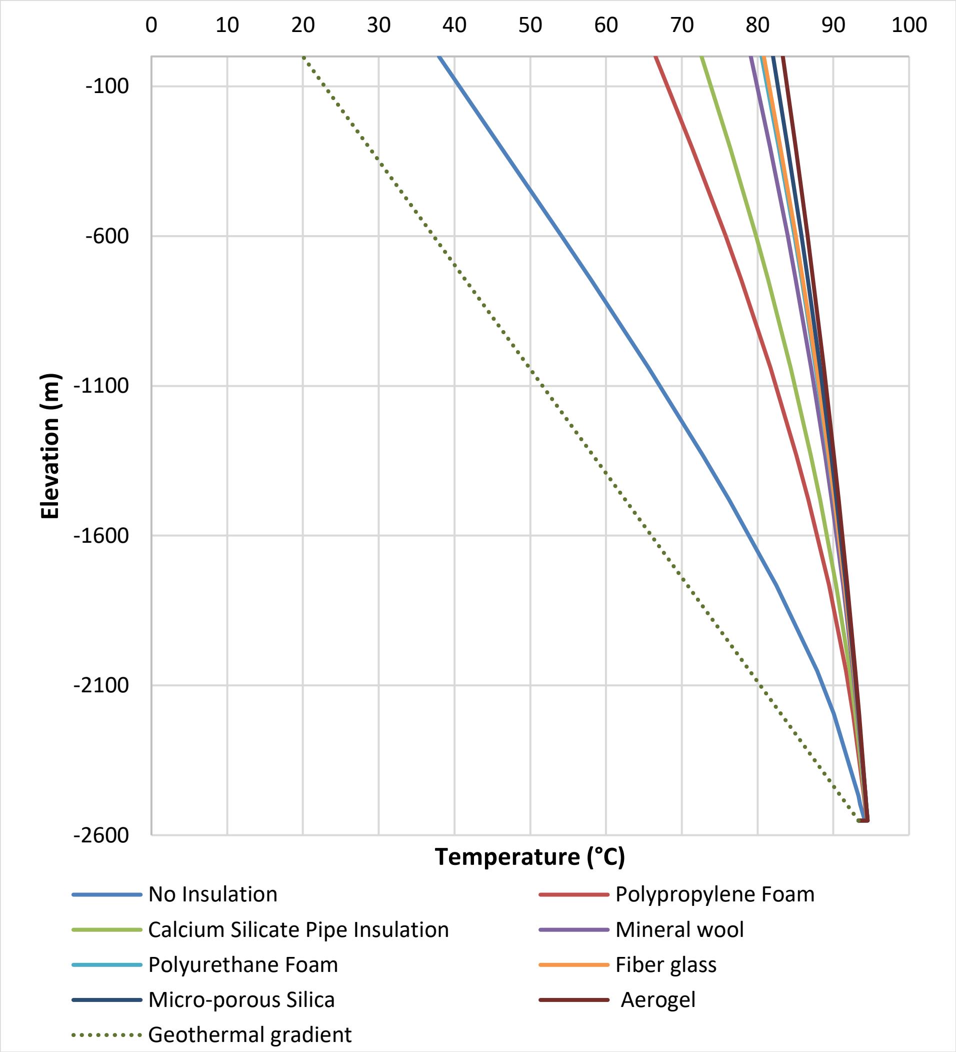


Figure 43: Temperature profile of the well for 0.25" external insulation (16°API)

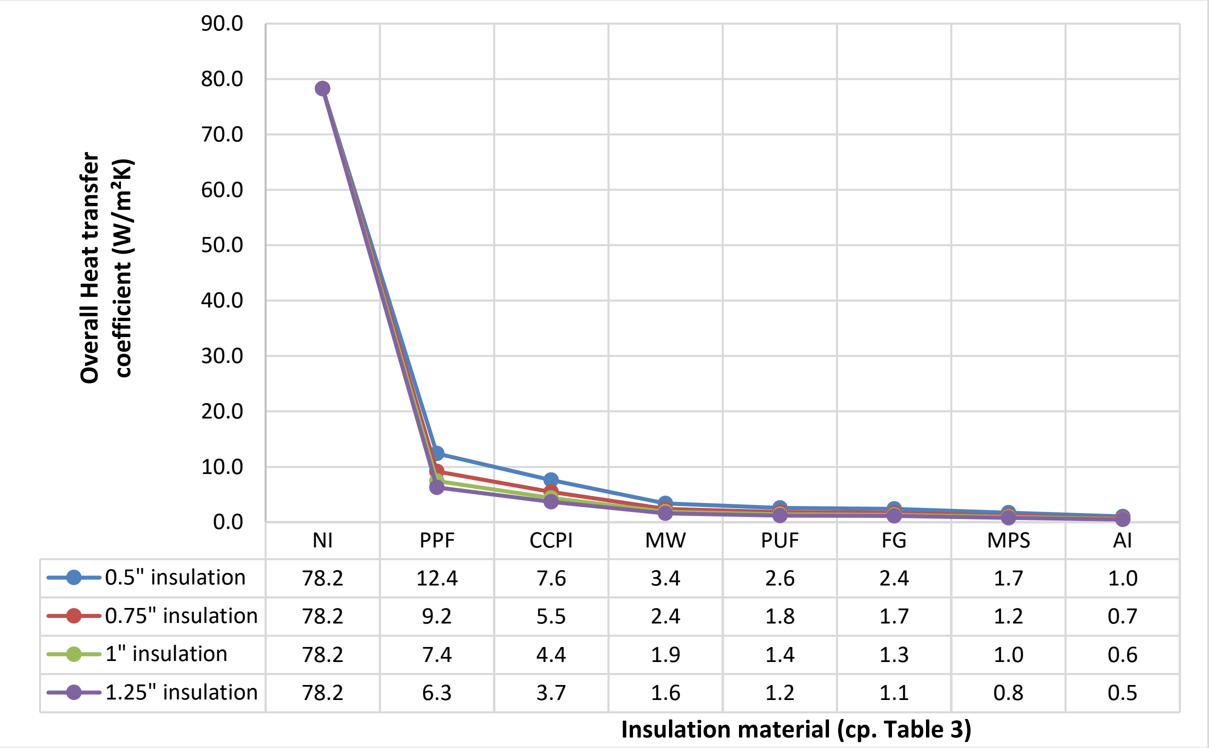
The increase of insulation thickness has decreased the temperature losses along the well. The highest drop was obtained in case of using 0.25” outside insulation, and the temperature profile of the well for this case is plotted in Figure 43. The overall heat transfer coefficient of each insulation material has reached its minimum value when using the highest insulation thickness, which has affected the temperature losses of the well. For instance, the temperature losses have been reduced from 94°C to 66°C in case of polypropylene foam, which is 10°C less than 0.1” insulation. The lowest temperature drop was reached in case of aerogel due to having the lowest overall heat transfer value. The temperature has decreased by only 11°C from 94°C to 83°C. The decrease in temperature losses has increased the output temperature in all cases of insulation materials. The output temperature has varied between a minimum of 66°C and a maximum of 83°C.

To sum up, using a 0.25” outside insulation keeps the fluid at a temperature higher than 66°C and decreases the temperature losses by a minimum of 30°C.

4.3.3 Extended external insulation

In this section, the insulation thickness will increase to values higher 0.25” that cannot be applied inside the tubing due to internal diameter size (3.548”). Therefore, the simulation was run only in case of external insulation of the tubing.

First, the overall heat transfer of the well is calculated in case of external insulation for four-insulation thicknesses, which are 0.5”, 0.75”, 1” and 1.25”.



	NI	PPF	CCPI	MW	PUF	FG	MPS	AI
0.5" insulation	78.2	12.4	7.6	3.4	2.6	2.4	1.7	1.0
0.75" insulation	78.2	9.2	5.5	2.4	1.8	1.7	1.2	0.7
1" insulation	78.2	7.4	4.4	1.9	1.4	1.3	1.0	0.6
1.25" insulation	78.2	6.3	3.7	1.6	1.2	1.1	0.8	0.5

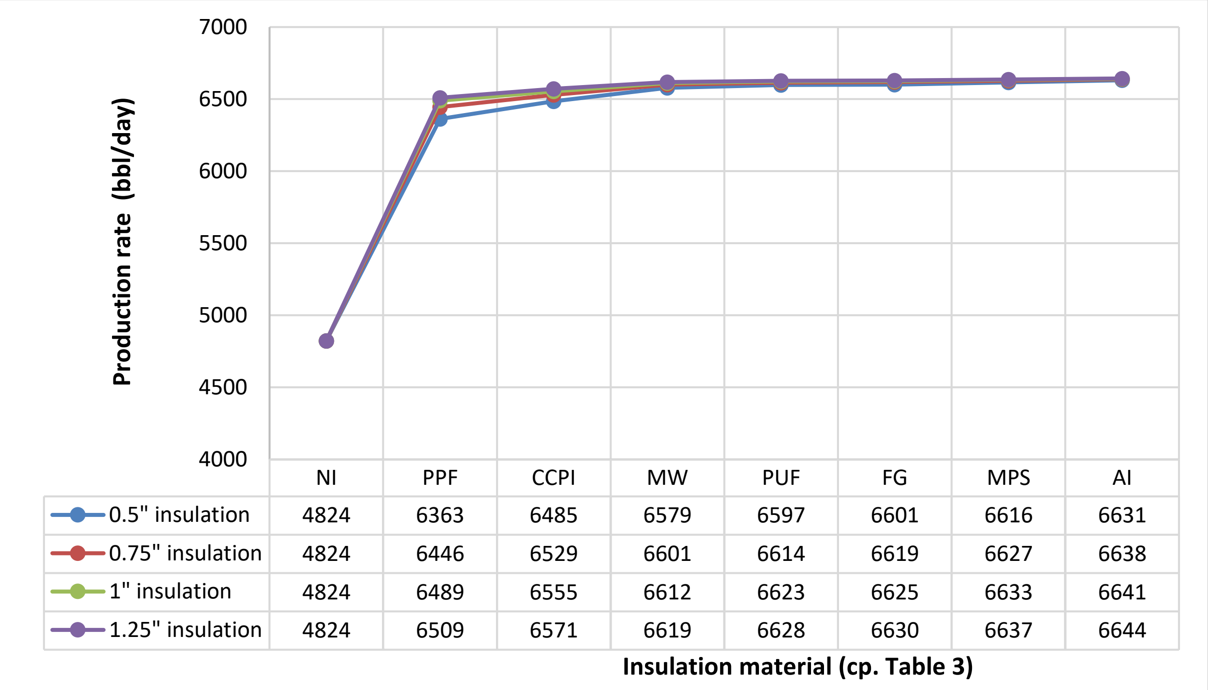
Figure 44: Overall heat transfer of the well for external insulation (16°API)

The abbreviations shown in the figure refers to Table 3 (chapter 2.6 p18). Figure 44 shows the generated results of overall heat transfer of the well for the different cases. The overall heat transfer of the well has decreased as the insulation thickness has increased. In case of 0.5” external insulation, the overall heat transfer has been reduced from 78.2 W/m²K to a minimum of 12.4 W/m²K in case of polypropylene foam, which is 6.5 times less. The overall heat transfer decreases more for insulation materials having lower thermal conductivities. Five insulation materials had values lower than one, which are mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel. The lowest reduction was from 78.2 W/m²K to 1 W/m²K in case of aerogel.

Increasing the insulation thickness to 0.75” has reduced more the overall heat transfer of the well but with different degrees depending on the insulation material. In fact, the reduction was more significant for insulation materials having the higher thermal conductivities such as polypropylene foam, mineral wool, and calcium silicate. The reduction of overall heat transfer from increasing the insulation to 0.75” decreases as the thermal conductivity drop between the insulator materials. The plot of 0.75” shows that the overall heat transfer was reduced to a minimum of 9.1 W/m²K (polypropylene foam) and to a maximum of 0.7 W/m²K (aerogel).

In case of 1” insulation, the overall heat transfer has been reduced by at least ten times. The plot of 1” isolation shows that all the insulation materials except the polypropylene foam had an overall heat transfer lower than 5 W/m²K.The lowest heat losses were obtained in case of using 1.25”. The overall heat transfer has decreased by at least 12 times to a minimum of 6.3 W/m²K (polypropylene foam) and to a maximum of 0.4 W/m²K (aerogel).

The production rate results of different insulation thicknesses are plotted in Figure 45 for different insulation materials.



	NI	PPF	CCPI	MW	PUF	FG	MPS	AI
0.5" insulation	4824	6363	6485	6579	6597	6601	6616	6631
0.75" insulation	4824	6446	6529	6601	6614	6619	6627	6638
1" insulation	4824	6489	6555	6612	6623	6625	6633	6641
1.25" insulation	4824	6509	6571	6619	6628	6630	6637	6644

Figure 45: Production rate of the well for external insulation (16°API)

For 0.5” external insulation, the production rate has increased from 4824 bbl/day to a minimum of 6363 bbl/day and a maximum of 6631 bbl/day, which results in a production gain between

31.5% and 37.5%. Increasing the insulation thickness from 0.5” to 0.75” has resulted in a relatively low increase of production rate especially for low thermal conductivities materials such as mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel. Adding 0.75” external insulation to the tubing has secured an increasing percentage of production rates varying between 33.6% and 37.6%. In case of 1” external insulation, the amount of increase of production rate is relatively low in comparison to 0.75” insulation. In fact, the production gain was less than 11 bbl/day, which is very low and negligible amount. In comparison to no insulation case, the production rate has increased from 4828 bbl/day to a minimum of 6489 bbl/day and a maximum of 6641 bbl/day. Therefore, adding 1” external insulation to the tubing has led to a production gain between 34.5% and 37.67%.

For 1.25” external insulation, the production rate reached its maximum value for the different insulation materials. It has increased to a minimum of 6509 bbl/day in case of polypropylene foam and a maximum of 6644 bbl/day. Therefore, the increasing percentage of production was between 34.9% and 37.7%. Increasing the insulation thickness from 1” to 1.25” resulted in a relatively low production gain, which has varied between 3 bbl/day and 20 bbl/day.

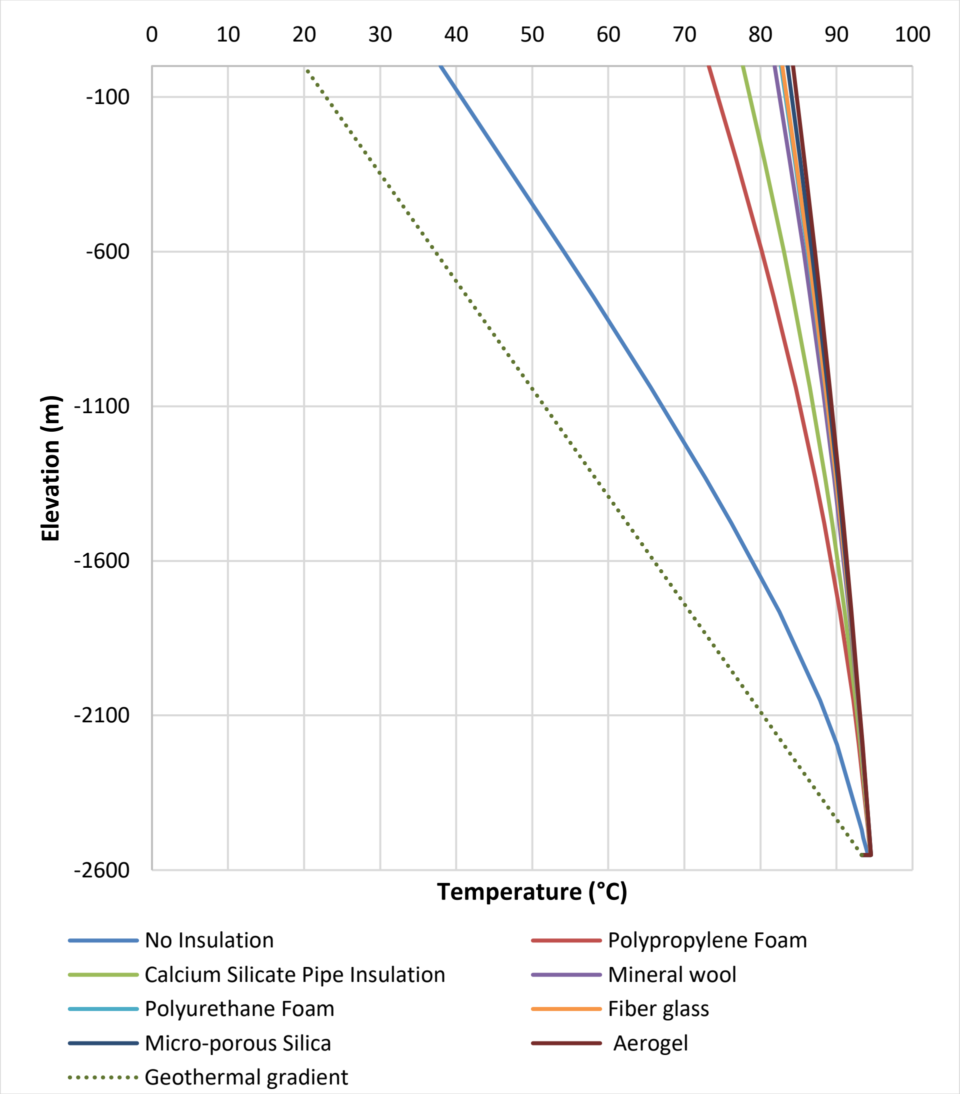


Figure 46: Temperature profile of the well for 0.5” external insulation (16°API)

The next output result generated from the simulation is the temperature profile. Figure 46 shows the temperature profile of the well in case of applying 0.5” insulation outside the tubing. The temperature losses along the wellbore have decreased as the insulation has increased to 0.5”. The maximum temperature drop was from 94°C to 73°C in case of polypropylene foam. Five insulation materials, which are mineral wool, polyurethane foam, fiberglass, microporous silica, and aerogel, had a very close temperature profile where the temperature has decreased from 94°C to a range between 83°C and 84°C.

Therefore, using 0.5” external insulation in 16°API oil well has kept the output temperature higher than 73°C and has decreased the temperature losses up to 10°C.

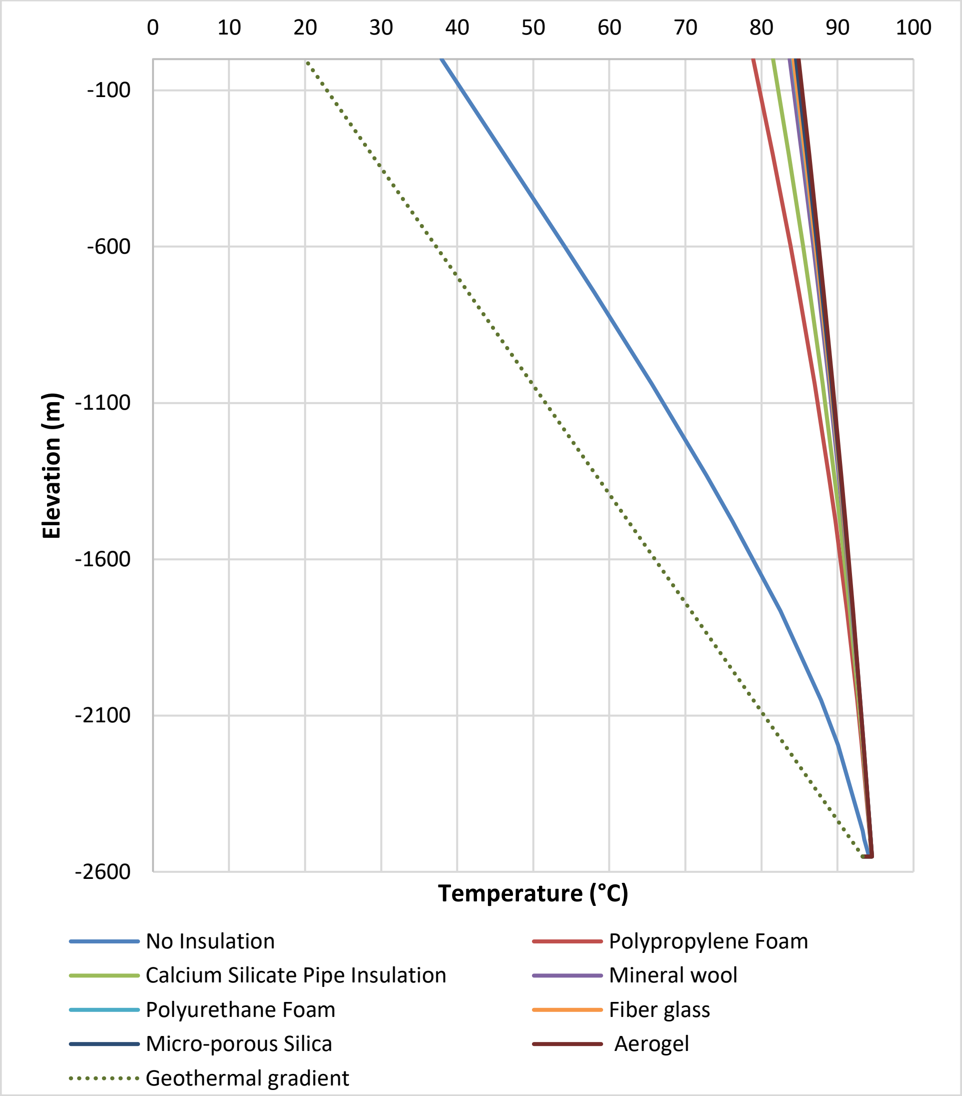


Figure 47: Temperature profile of the well for 1.25" external insulation (16°API)

Figure 47 shows the temperature profile of the well for 1.25” external insulation. Initially, the temperature has decreased from 94°C to 37°C while adding a 1.25” insulation has reduced it to a minimum of 79°C in case of polypropylene foam. Five insulation materials has nearly the same temperature profile as shown in Figure 47 which are the ones having the lowest thermal conductivities. Increasing the insulation thickness from 0.5” to 1.25” did not decrease the temperature losses significantly. In fact, the temperature losses were reduced by a maximum of 6°C in case of polypropylene foam and a minimum of 0.6°C in case of aerogel.

Therefore, adding 1.25” insulation had a relatively low effect on the temperature profile of the well especially for low thermal conductivities materials used.

4.4 Flow rate variation

In this section, the simulation is performed in PIPESIM software for different flow rates and overall heat transfer coefficients in order to examine its effect on the temperature and pressure losses of the well. Three different oil API gravities were used in the simulations, which are

- 36°API (light oil)
- 26°API (medium oil)
- 16°API (heavy oil)

The medium oil will be the case study in this section, and the simulation results of light oil and heavy oil will be presented in the appendices. Figure 48 shows the sketch of the well, which was used for the case study in this section.

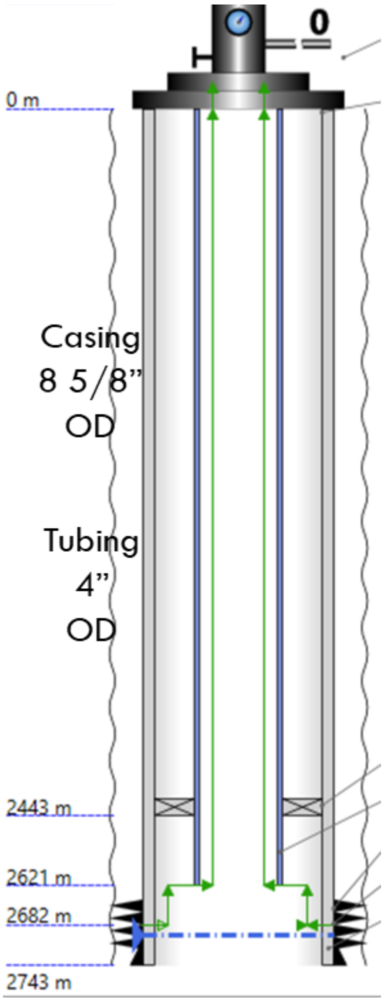


Figure 48: Sketch of the well

4.4.1 Overall heat transfer: 89.4 W/m²K (no insulation)

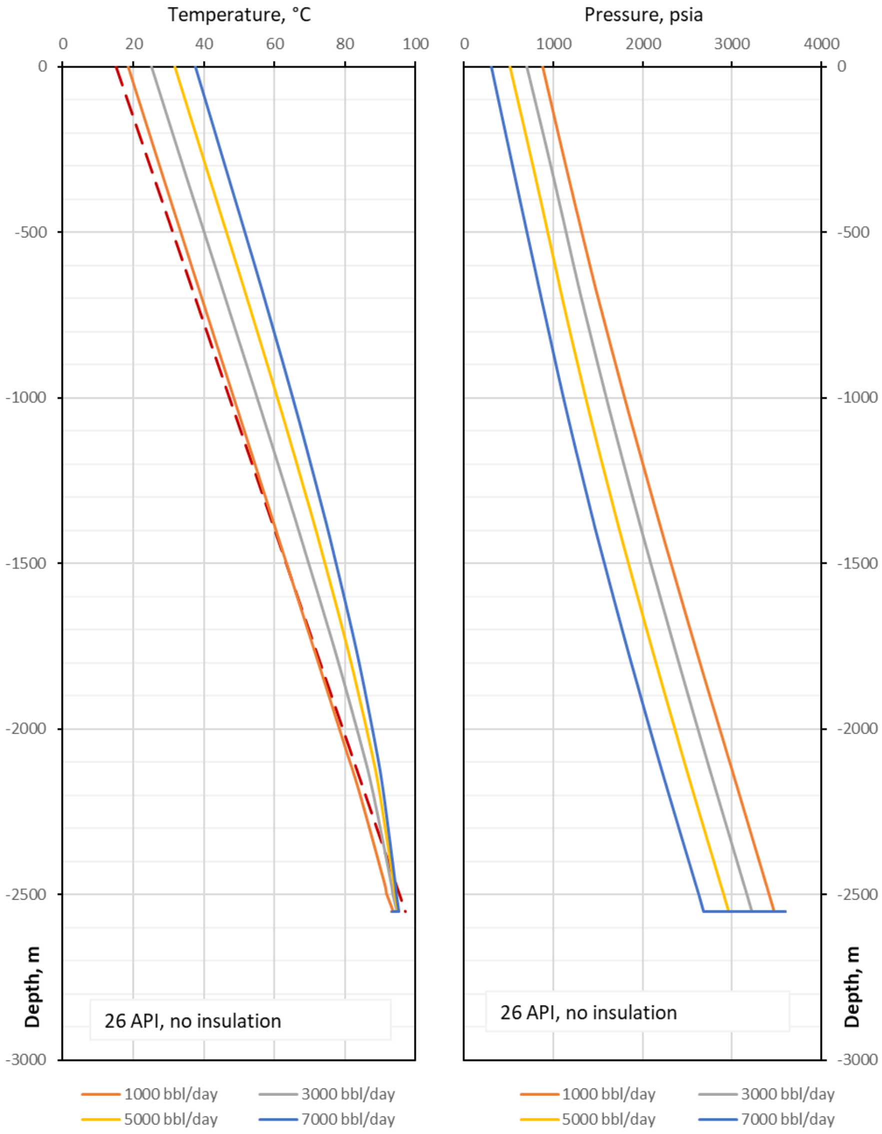


Figure 49: Temperature and pressure profile of the well (26 °API, 89.4 W/m²K)

Figure 49 shows the temperature profile and the pressure losses along wellbore in case of no insulation. The temperature profile in case of 1000 bbl/day flowrate was close to the geothermal gradient curve as the output temperature has differed by only 3.5°C from the ambient temperature. The increase of flow rate from 1000 to 3000 bbl/day has reduced the temperature losses by 7°C. In case of 5000 bbl/day, the temperature has decreased from 95°C to 31.8°C, which is 6°C less than the previous example. The lowest temperature losses were obtained in case of 7000 bbl/day, which is the highest flow rate. Regarding the pressure losses, it is noticed that the pressure losses increase with increasing the flow rate. For instance, the pressure has dropped from 3600 psi to 878 psi in case of 1000 bbl/day while it has decreased to 307 psi in case of 7000 bbl/day. An insulation material has to be installed in the tubing in order to reduce the overall heat transfer of the well.

4.4.2 Overall heat transfer: 34.1 W/m²K (0.25” polyurethane foam)

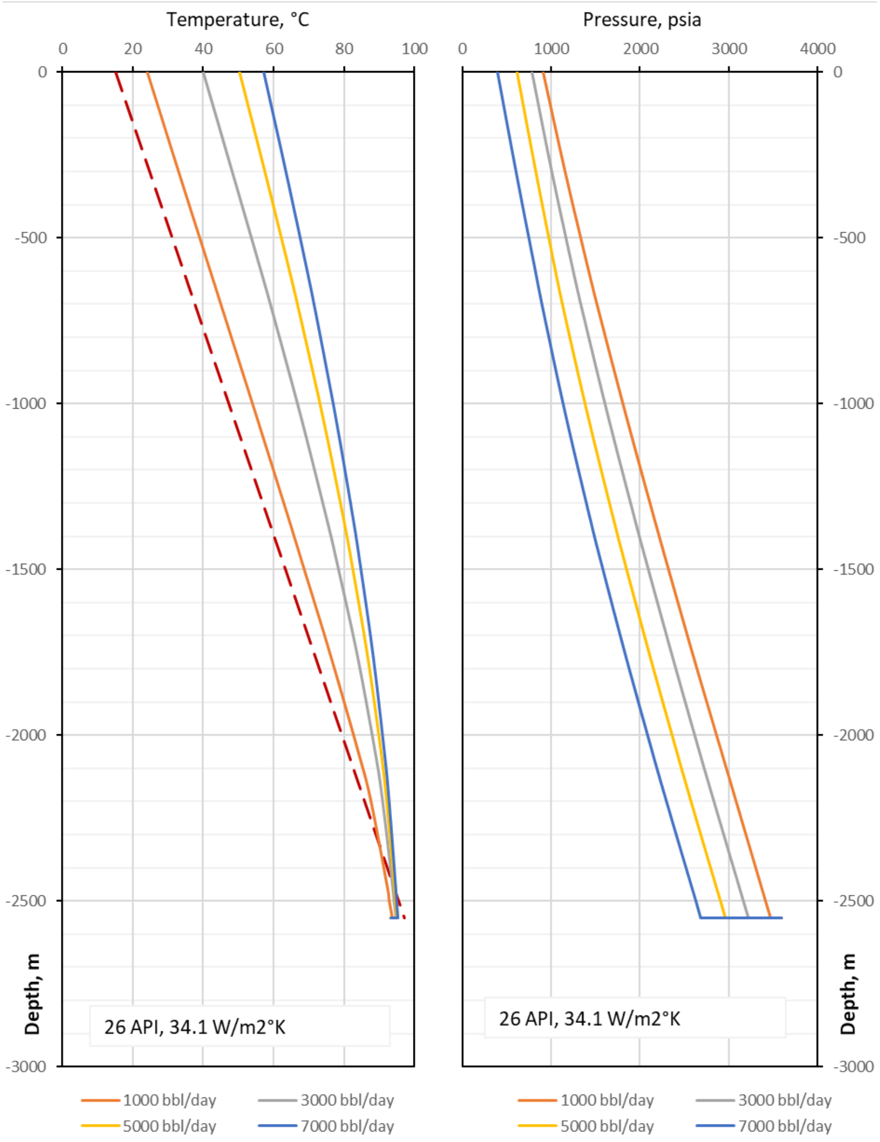


Figure 50: Temperature and pressure profile of the well (26 API, 34.1 W/m²K)

Figure 50 illustrates the temperature and pressure profile for different flowrate when the overall heat transfer has been reduced from 89 W/m²K to 34 W/m²K. The heat coefficient reduction was due to the thermal insulation of production tubing. The temperature and pressure losses have decreased compared to the no insulation case. In fact, the temperature has declined from 93.8°C to 24°C (18°C, no insulation) and the pressure has decreased from 3600 psi to 909 psi (878 psi, no insulation) in case of 1000 bb/day flow rate. The increase of the flow rate has resulted in a higher decrease of the temperature and pressure losses than the no insulation case. For instance, the temperature losses were reduced by 20°C and the outlet pressure has increased by 82 psi in case of 7000 bbl/day flow rate.

4.4.3 Overall heat transfer: 22.7 W/m²K (0.2” micro-porous silica)

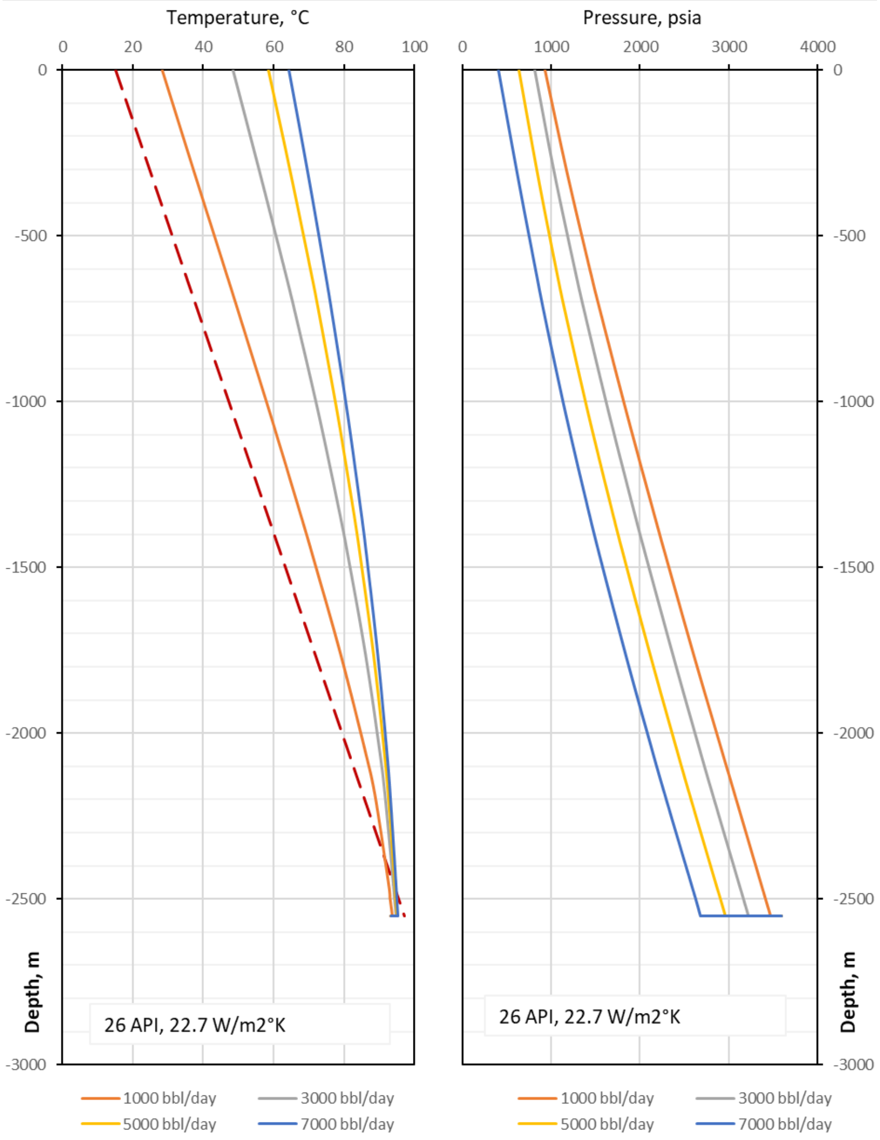


Figure 51: Temperature and pressure profile of the well (26 API, 22.7 W/m²K)

The overall heat transfer was reduced to 22.7 W/m²K due to using a lower thermal conductivity material or increasing the insulation thickness, which has influenced the temperature and pressure profile of the well shown in Figure 51. In fact, the temperature losses have decreased more than the previous case (34.1 W/m²K). For example, the temperature has declined from 97°C to 48°C (3000 bbl/day case) while it was 40°C in case of 34.1 W/m²K. As the flow rate increases, the temperature losses decrease more and more. The highest output temperature was obtained for 7000 bbl/day flow rate, which was 64.4°C. The pressure losses were reduced more due to the decrease of the overall heat transfer coefficient. For instance, the lowest pressure losses were obtained in case of 1000 bbl/day where the pressure has diminished from 3600 psi to 928 psi. As the flow rate increase, the pressure losses increase as well. The highest-pressure losses were obtained in case of 7000 bbl/day where the pressure has declined from 3600 psi to 406 psi. Therefore, increasing the insulation thickness or using an insulation material having a lower thermal conductivity than the previous case will result in lowering the temperature and pressure losses.

4.4.4 Overall heat transfer: 11.4 W/m²K (0.25” aerogel)

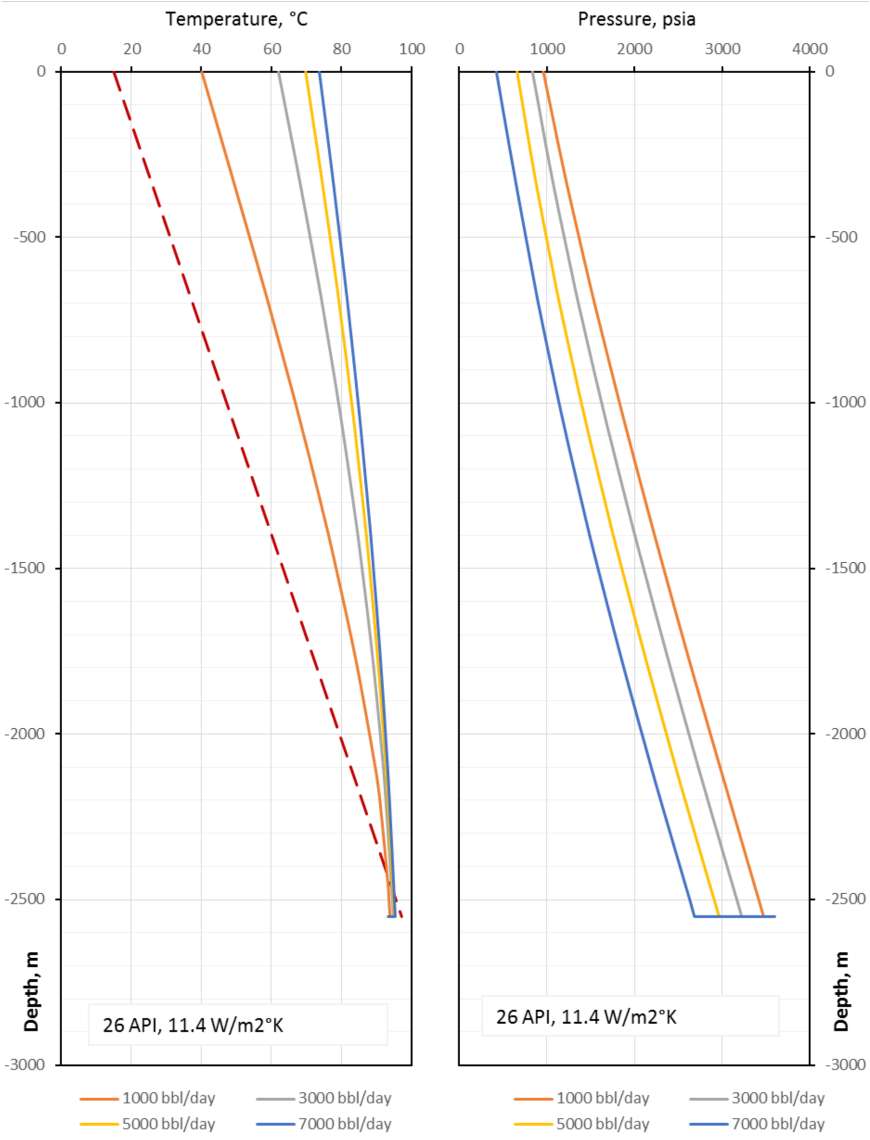


Figure 52: Temperature and pressure profile of the well (26 API, 11.4 W/m²K)

The decrease of the overall heat transfer is justified by either using an insulation material having a lower thermal conductivity or by increasing the insulation thickness. Figure 52 shows the temperature profile and pressure losses along the wellbore for an 11.4 W/m²K overall heat transfer coefficient. It is noticed that the temperature losses have decreased due to heat transfer reduction. For a low flow rate (1000bbl/day), the temperature has declined from 93.8°C to 40°C, which has increased by 22°C in comparison to no insulation case. Figure 52 illustrates that the temperature losses decrease as the flow rate increases. The highest flow rate, which was 7000 bbl/day, has resulted in the lowest temperature drop from 95°C to 73°C. The pressure losses were also reduced as the overall heat transfer of the well has decreased from 22.7 W/m²K to 11.4 W/m²K. For instance, the pressure has decreased from 3600 psi to 423 psi (1000 bbl/day) to 660 psi (3000bbl/day) to 835 psi (5000bbl/day) and to 959 psi (7000bbl/day). It is noticed that the pressure losses have declined in comparison to the previous case.

4.4.5 Overall heat transfer: 2.8 W/m²K (1.25” aerogel)

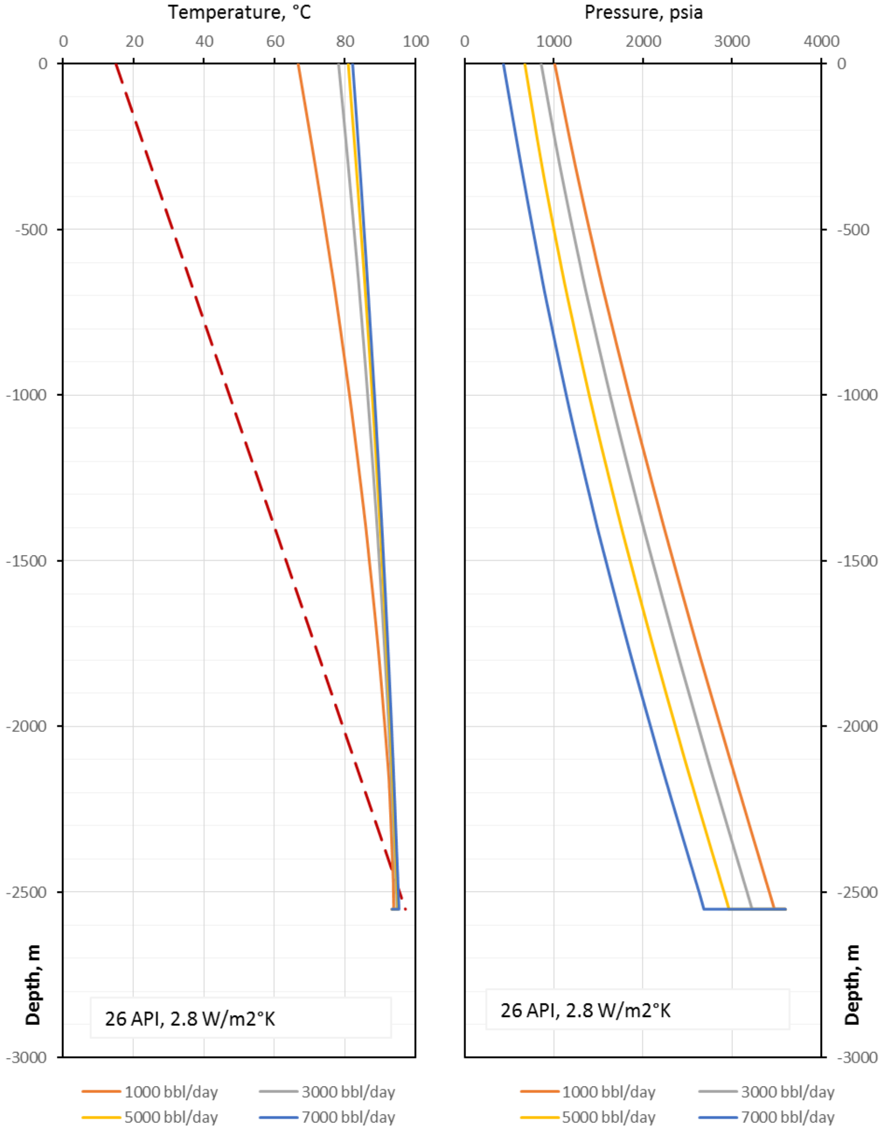


Figure 53: Temperature and pressure profile of the well (26 API, 2 W/m²K)

The overall heat transfer was reduced by 32 times in comparison to no insulation case. The output temperature was preserved above 60°C for the different flow rate values. The temperature had declined to only 66.7°C when the flow rate was 1000 bbl/day. The temperature profile of the rest of flowrates was very close, as the output temperature has varied between 78.2°C and 82.2°C. It is noticeable that the pressure losses were lower than the previous case as the overall heat transfer have decreased to 2.8 W/m²K. For instance, the pressure has dropped from 3600 psi to 1011 psi for 1000 bbl/day flowrate while it was 959 psi in the previous case (11.4 W/m²K). To sum up, the lowest pressure and temperature losses were obtained in this case due to having the lowest overall heat transfer coefficient.

To sum up, insulating the production tubing has decreased the temperature and pressure losses significantly. Insulating the tubing can be an alternative solution to minimize the heat losses in the wellbore.

5 Conclusion and summary

The simulation was run for three different types of oil which are light oil (36°API), medium oil (26°API), and heavy oil (16°API). The thermal insulation has influenced all the three types of produced fluids but with different degrees.

In fact, the most influenced one was the heavy oil where the production gain has varied between 13.1% and 37.1% in case of inside insulation and between 11.5% and 37.7% in case of external insulation of tubing. Besides, the production increase for medium oil was between 10% and 20.9% in case of internal insulation and between 9.3% and 21.1% in case of external insulation. The light oil was the least influenced one in term of production where the gain was between 2.5% and 6.16% in case of internal insulation and between 2.3% and 6.26% in case of outside insulation.

Table 12: Summary of production gain results for different case studies

Insulation material	Light oil (36°API)		Medium oil (26°API)		Heavy oil (16°API)	
	Min prod. gain	Max prod. gain	Min prod. gain	Max prod. gain	Min prod. gain	Max prod. gain
PPF	3.20%	5.70%	12.70%	19.80%	18.60%	34.90%
CSPI	4.00%	6.00%	15.30%	20.40%	24.60%	36.20%
MW	5.10%	6.20%	18.30%	20.90%	31.50%	37.20%
PUF	5.40%	6.20%	18.90%	21.00%	33.00%	37.40%
FG	5.40%	6.20%	19.10%	21.00%	33.30%	37.40%
MPS	5.70%	6.20%	19.60%	21.00%	34.60%	37.60%
AI	5.90%	6.30%	20.20%	21.10%	35.80%	37.70%

The abbreviations shown in the table refers to Table 3 (chapter 2.6 p18). Table 12 illustrates the summary of the results of production gain from different insulation materials in case of light, medium, and heavy oil. The least performing material in term of production gain was the polypropylene foam while the best performing material was the aerogel.

Figure 54, Figure 55 and Figure 56 illustrates how the production gain has differed from one well to another. In light oil well, the production gain from 0.2” insulation has varied between 4.2% and 6.1%. However, the production has increased by a minimum of 15.7% and 20.8% in case of 0.2” insulation of medium oil well. Moreover, the increase in production was more significant in heavy oil well where it has varied between 25.5% and 36.9%.

Based on the results generated from the simulations, the internal insulation of tubing has always shown lower heat losses than external insulation in case of using a thickness between 0.05” and 0.25”. Consequently, the inside insulation has resulted in higher production rates and lower temperature losses than external insulation when using the same insulation thickness.

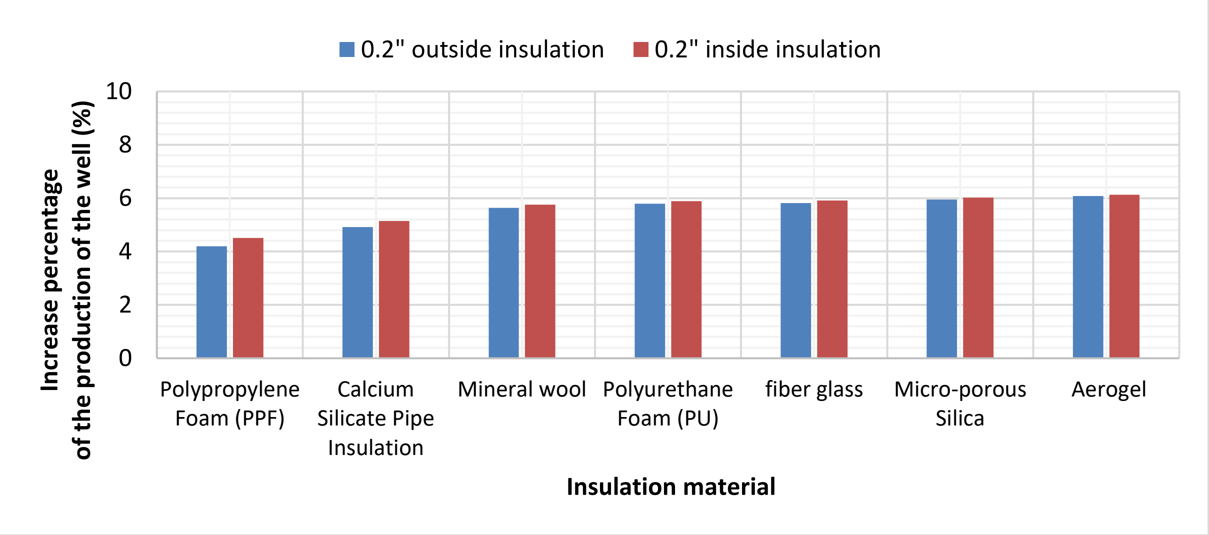


Figure 54: Production gain percentage from 0.2" insulation in light oil well (36°API)

Figure 54 represents the production gain in light oil well for 0.2” insulation outside and inside the tubing. Internal insulation has resulted in higher production rate than external insulation. For instance, the production gain has improved from 4.19% to 4.5% in case of polypropylene foam from outside to inside insulation.

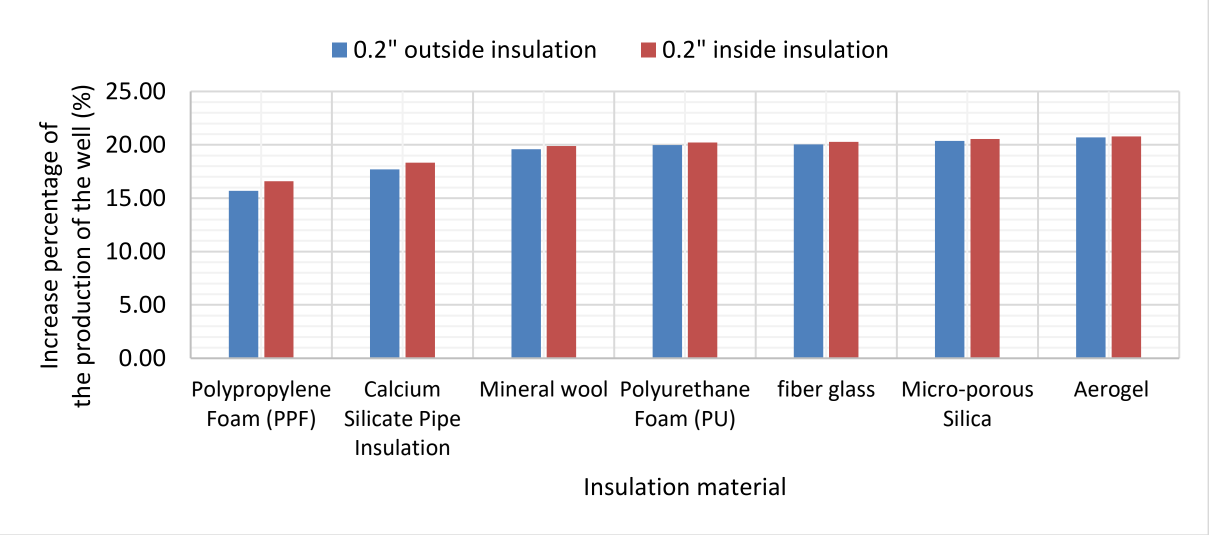


Figure 55: Production gain percentage from 0.2" insulation in medium oil well (26°API)

Figure 55 shows the increase percentage of production for the medium oil well in case of 0.2” insulation for both inside and outside the tubing. The production has increased more in case of internal insulation of tubing for all insulation materials used. The production of the well has increased by 1% when using inside insulation instead of external insulation in case of polypropylene foam.

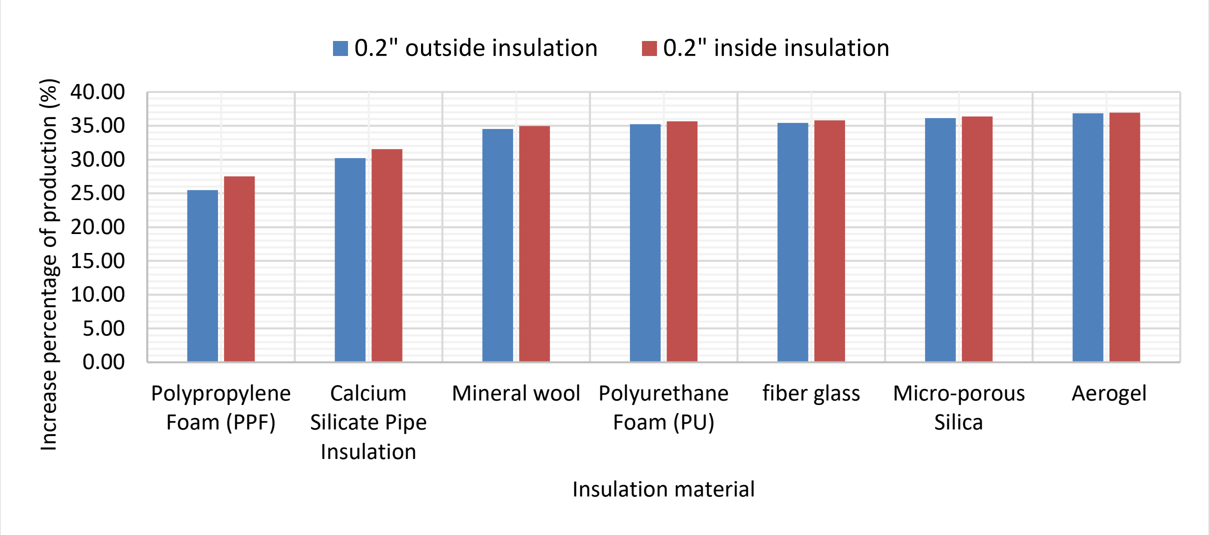


Figure 56: Production gain percentage from 0.2" insulation in heavy oil well (16°API)

Figure 56 demonstrates the production gain in heavy oil from the internal and external insulation of the tubing. The inside insulation has provided higher production rate than external insulation. For instance, the production rate has improved from 25.5% to 27.5% in case of polypropylene foam.

Therefore, it is recommended to use internal insulation when using a small insulation thickness, which was between 0.1” and 0.25” in the case study.

The inside insulation thickness was limited to 0.25” due to inside diameter of the tubing. Thus, the insulation was simulated outside the tubing for thicknesses higher than 0.25”. In this case, the external insulation has shown better results than the internal insulation. In fact, the production rate has increased more, and the temperature losses have decreased more when using external insulation thickness varying between 0.5” and 1.25” in the case study. Therefore, using high external insulation thickness can show greater output temperatures and production rates than inside insulation.

Thermal insulation of tubing has as well reduced the temperature losses along the wellbore for the three different types of oil. The decrease of temperature losses has differed from one oil type to another, but the difference was small. In all cases, the fluid output temperature was preserved to a minimum value of 60°C and a maximum value of 84°C depending on the insulation material type and thickness.

The increase of insulation thickness has resulted in the reduction of overall heat transfer coefficient but to a certain extent only. The thicker the insulation is, the lower heat losses are.

The decrease of overall heat transfer has influenced the production rate and the temperature profile of the well. In fact, the generated results from the simulation have shown that the production rate has increased with increasing insulation thickness. The temperature losses have decreased with an increase of insulation. The effect of thickness has differed from one insulation material to another and the simulation results has shown that the insulators having the higher thermal conductivities are more influenced than the lower ones. Therefore, the selection of insulation thickness will depend on the type of insulation material, on the tubing and annulus size.

The scope of the thesis was to evaluate different tubing insulation materials and their effect on the production rate and the heat losses along the wellbore. The insulation materials were investigated inside and outside the tubular. The conservation of temperature of the fluid allows avoiding the precipitation of asphaltene and paraffin that cost the industry millions of dollars in lost production and cleaning operations.

Several insulation materials with different thermal conductivities values have been used for the simulation. The calculations of the overall heat transfer of the well have proven that it decreases with decreasing thermal conductivity value.

Aerogel and micro-porous silica have shown better results in comparison to the other insulation materials in terms of higher production rates and the lower heat losses. In addition, it was found that the materials having the lowest thermal conductivities have given the best output results.

Increasing the insulation thickness has decreased the heat losses and increased the production rate of the well up to a maximum point where it is no longer affecting the results. Therefore, it is essential to select the optimum thickness based on the simulation results. This optimum thickness value is varying depending on the insulation material used and on the space available for insulating in the tubing.

For an insulation thickness between 0.1” and 0.25”, internal insulation showed better production rates and lower temperature losses than the external case. However, external insulation can be installed for thicknesses higher than 0.25”, which is not possible in the case of internal insulation due to size limitation of inside diameter of the tubing.

The simulation using PIPESIM software was run for three different scenarios: light oil (36°API), medium oil (26°API) and heavy oil (16°API). Regarding the production of the well, the lowest impact of insulation was observed in the case of light oil, where the production gain did not exceed 6.2%. The medium oil well has shown a higher increase in production rate that reached 20%. Furthermore, the most promising results were obtained in the case of heavy oil where the production gain surpassed 37%.

Insulating the production tubing has conserved the output temperature significantly and kept it above a minimum value of 55°C in all cases. For a maximum insulation thickness of 1.25” externally, the temperature losses from the reservoir to the surface did not exceed 20°C.

The insulation material type, its thickness and its position either inside or outside the tubular are the most important parameters to select in designing a successful tubing insulation system in terms of reducing the heat loss hence better production rates.

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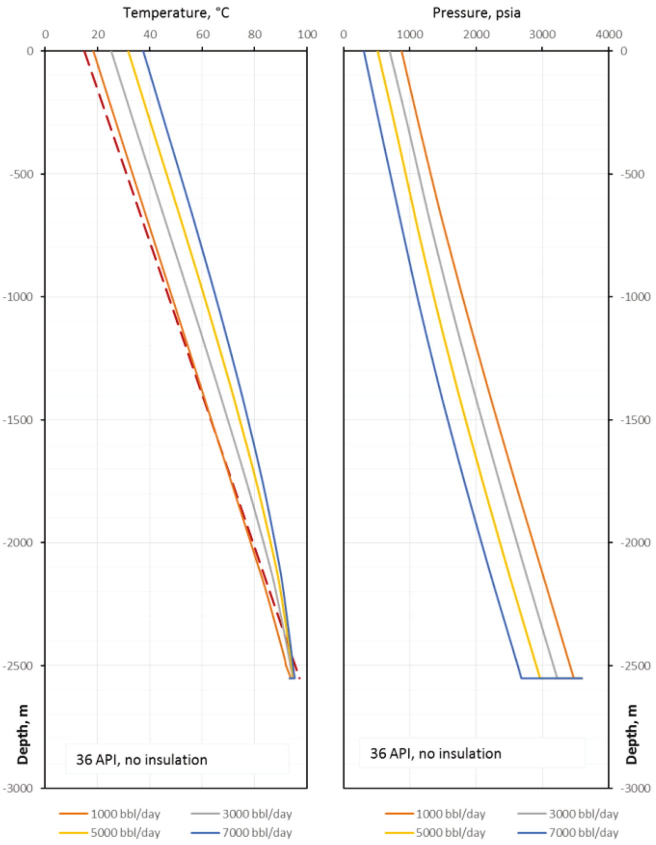
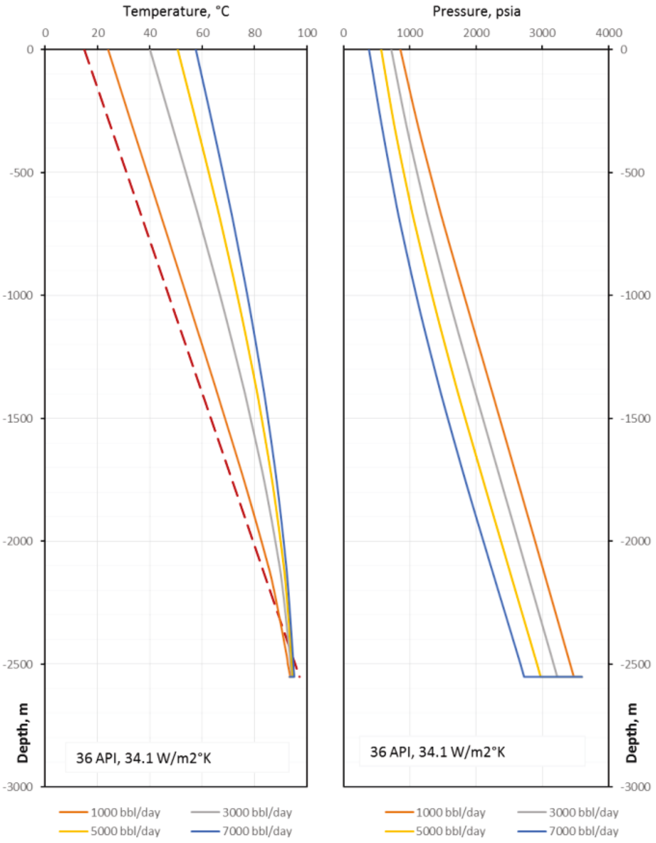
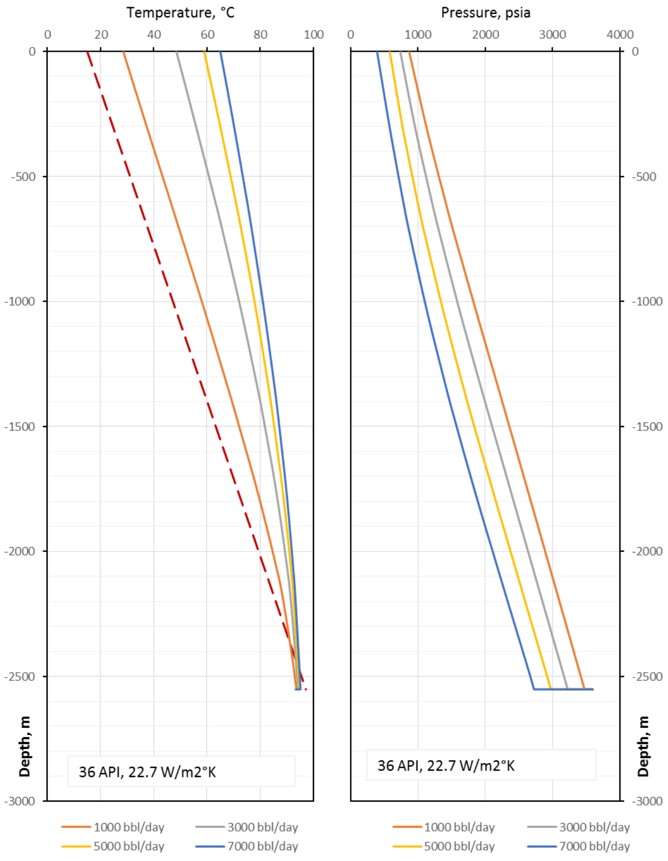
7 Appendix

7.1 Flow rate variation Light oil (36 API)



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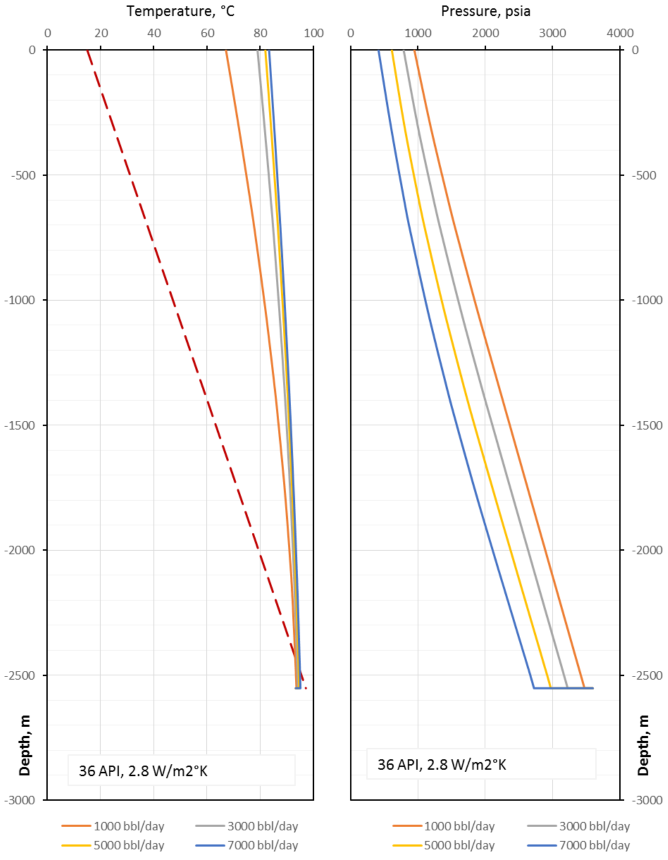
Pressure, psia
0 1000 2000 3000 4000
0 -500 -1000 -1500 -2000 -2500 -3000
Depth, m
36 API, 22.7 W/m2°K
36 API, 22.7 W/m2°K
1000 bbl/day
3000 bbl/day
5000 bbl/day
7000 bbl/day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Pressure, psia
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0 -500 -1000 -1500 -2000 -2500 -3000
Depth, m
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36 API, 2.8 W/m2°K
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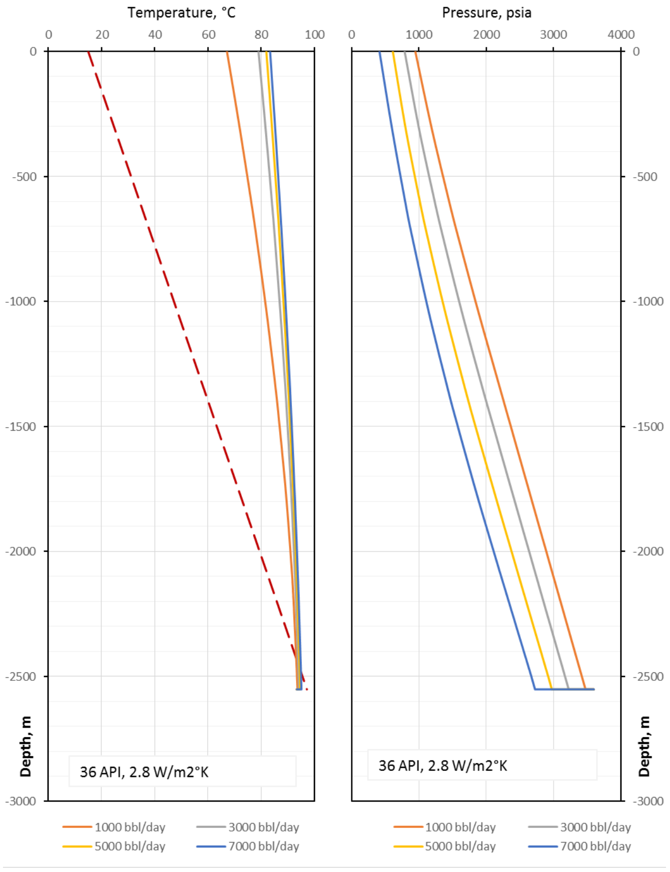
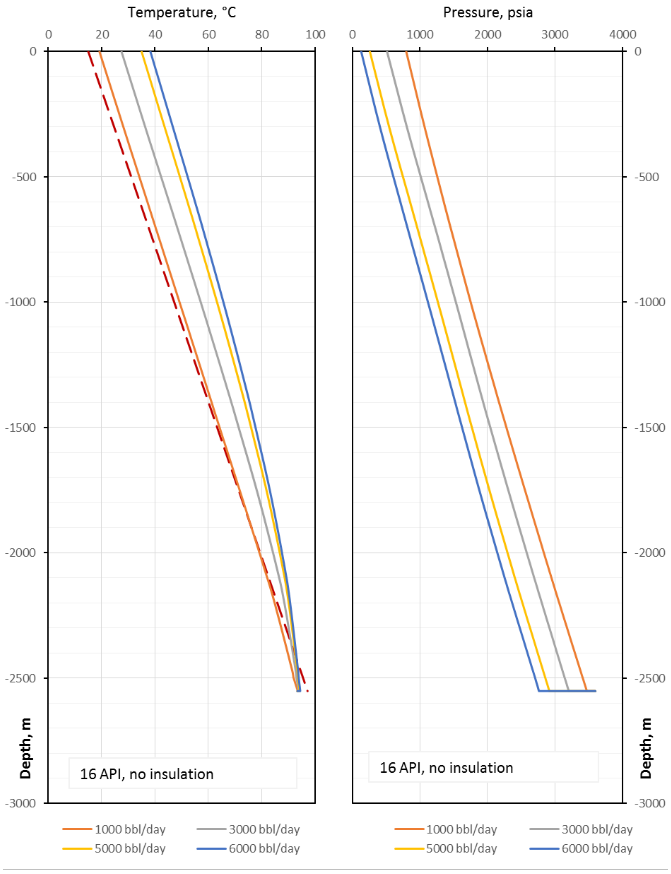
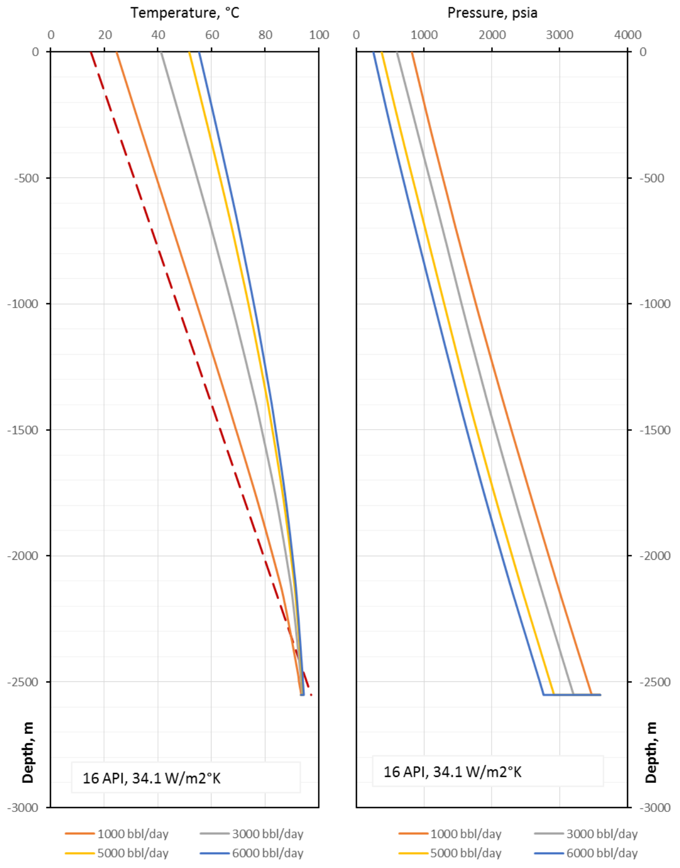
3000 bbl/day
5000 bbl/day
7000 bbl/day



7.2 Flowrate variation heavy oil (16 API)

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60
80
100
Pressure, psia
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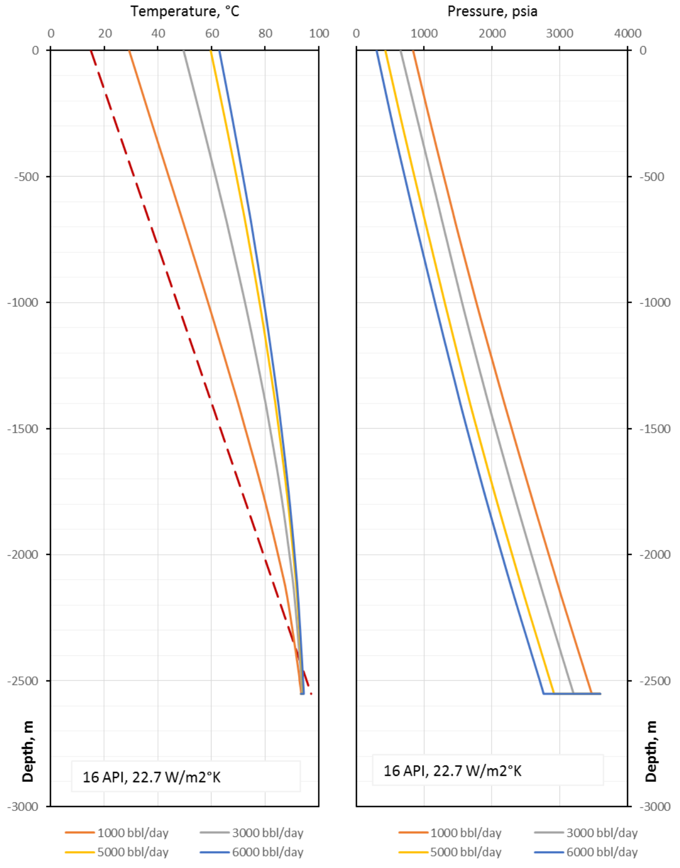
1000
2000
3000
4000
0
-500
-1000
-1500
-2000
-2500
-3000
Depth, m
16 API, 34.1 W/m2°K
16 API, 34.1 W/m2°K
1000 bbl/day
3000 bbl/day
5000 bbl/day
6000 bbl/day


Temperature, °C
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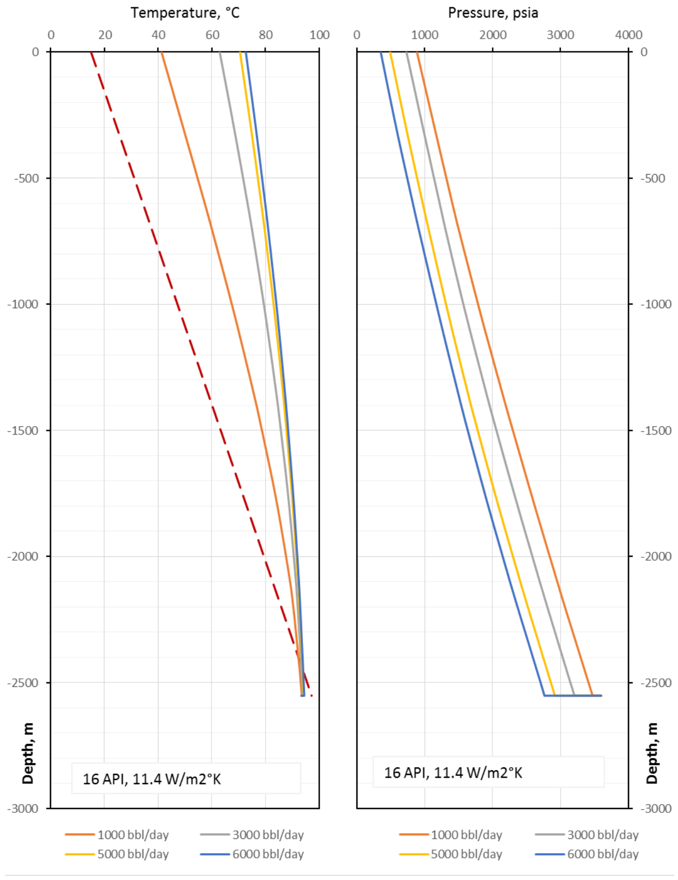
20
40
60
80
100
Pressure, psia
0
1000
2000
3000
4000
0
-500
-1000
-1500
-2000
-2500
-3000
Depth, m
16 API, 22.7 W/m2°K
16 API, 22.7 W/m2°K
1000 bbl/day
3000 bbl/day
5000 bbl/day
6000 bbl/day


Temperature, °C
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Pressure, psia
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-500
-1000
-1500
-2000
-2500
-3000
Depth, m
16 API, 11.4 W/m2°K
16 API, 11.4 W/m2°K
Depth, m
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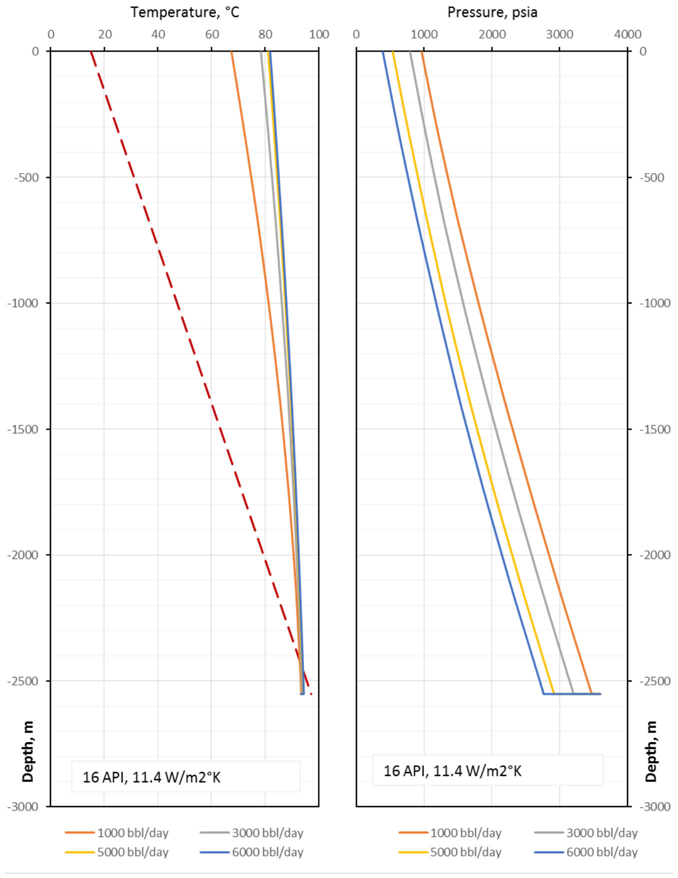
3000 bbl/day
5000 bbl/day
6000 bbl/day
1000 bbl/day
3000 bbl/day
5000 bbl/day
6000 bbl/day


Temperature, °C
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Pressure, psia
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-500
-1000
-1500
-2000
-2500
-3000
Depth, m
16 API, 11.4 W/m2°K
16 API, 11.4 W/m2°K
Depth, m
1000 bbl/day
3000 bbl/day
5000 bbl/day
6000 bbl/day
1000 bbl/day
3000 bbl/day
5000 bbl/day
6000 bbl/day