Aerosols in gas transporting systems

Master Thesis

by

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Affidavit

Herewith I declare in the lieu of oath that this thesis is entirely of my own work using only literature cited at the end of this volume

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To my parents Franz and Monika Huber

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1. Abstract

The transport of gas from regions beyond Europe has increased in the last years due to the growing energy demand. Therefore problems concerning the gas transport are of utmost importance. One problem is the existence of fluids in gas transporting systems and also at the end customers, although drying units and separators are installed at the compressor stations and branching points. The objective of this thesis is to show possible scenarios for the generation of fluids in dry gas, which fulfils certain quality standards like limitations of dew points. Further investigations are the conditions for liquid hold up and the transport of fluid in pipelines through these units. Moreover the flow regime of these fluids is analyzed to verify that these liquids are really transported as aerosols.

The practical part of this work is done for the Trans Austrian Gas (TAG) system, which transports dry gas. Key findings are that heavy hydrocarbons above C_{6+} have a significant impact on the phase diagram of the gas, although their fraction is in the range of 0.1% of the total gas composition. For this reason the influence of entrained sealing oil at gas compressors on the phase diagram is researched. Another fluid, which can be found in pipelines, is glycol. Its phase behaviour and the possible formation of aerosols is tested.

Another finding is that the geometry of the pipeline system influences the flow of liquids dependent on the flow regime. This again has an effect on the overall phase diagrams of the fluid stream in the single branches and can contribute to the liquid generation.

A phenomenon that is also discussed is that fluids cannot always be found at the same places in a pipeline system. Reasons for the vanishing of liquid are presented and improved solutions for the reduction of possible fluids are given.

2. Theoretical Background

2.1. General information on natural gas

Natural gas is produced out of geological formations and consists mainly of methane. Dependent whether it is associated gas, non associated gas or comes from a different source, the composition of natural gas changes. The other components are heavier hydrocarbons, nitrogen, hydrogen, sulphur dioxide and carbon dioxide. These are the parts of the gas, which should be removed, because otherwise corrosion and liquid drop out can lead to fatal disasters. The amount of Nitrogen is normally also decreased, because of its non existing heating value. Therefore the amount of these additional gases in the main stream is regulated in contracts.

Non associated gas is the natural gas that is produced from pure gas wells and contains only traces of hydrocarbons heavier than pentane. In contrast to this case, associated gas is the additional product in oil production and is a so called “rich gas” that is fully loaded with heavy hydrocarbons. Due to the different qualities of the gas it has to be processed before it reaches the specifications of most contracts. When the gas then complies with the specifications, it can be transported by the transmission pipeline system.

These processes start directly after the wellhead and include not only the removal of the undesired gases, but also the decrease of the water content and solids if present. The reduction of the unwanted parts of the gas is not perfect and therefore the gas is sensitive to pressure and temperature changes during the transport, which can lead to the generation of liquids. A significant impact on this generation can have the ambient temperature, which can decrease the gas temperature below the dew points. Another important issue on this topic is that pressure reduction can also reduce the temperature due to Joule Thomson effects.

The mentioned events lead to condensation of liquids in gas transmission pipelines, which can be a significant problem, because these fluids are present in the physical form of aerosols, which are complicate to filter out. Therefore they can accumulate in undesired areas and can cause failures of machineries during the transport and at the customer.

Due to the fact that the worldwide gas consumption is steadily increasing and that the largest gas reserves are often situated far away from the consumers, the transport of the gas is of crucial importance. For this reason problems connected with the transport is an object of high interest for the industry and the research.

2.2. Introduction to aerosol science

Aerosols are a fine mixture of liquid droplets and grains in a gas. They have been studied through the last century till now. Their importance is not negligible because of their use in pharmaceuticals, chemicals and many other industries. In the last years the focus in aerosol science was the meteorology, because of the crucial role of aerosols in global warming.

Generally speaking it has to be said that aerosols are a dynamic constantly changing system of small particles in a carrier gas. Their behaviour is dependent on the gas, on the kind of particle and on the particle size distribution.

A very common classification of aerosols according to Parker C. Reist(1) is the division by physical properties into:

1. **dust**: consists of solids generated by crushing, grinding, blasting; the size ranges from sub microscopic to visible; they are small copies from a parent material
2. **fume**: solid particles made by combustion, sublimation or distillation; small sized only up to one µm
3. **smoke**: an aerosol normally produced via a burning process, where the combustion process is incomplete; the size of the particles is in the same region like fumes
4. **mist and fog**: liquid aerosols, which are produced by evaporation of liquid or condensation of vapour; the size is normally in between sub microscopic to 20 µm, but can coagulate to 100 µm; therefore they can glide on air currents
5. **bio aerosol**: an aerosol consisting of living organisms like bacteria or viruses

This first subdivision is often not helpful to characterize the physical properties of an aerosol adequate enough. Therefore further parameters have to be defined.

Particle size is one of the most important factors to classify aerosols. The measurement of this is often quite difficult, because of the non spherical shape of most solid aerosols. Generally only liquid particles form real spheres. Therefore an equivalent diameter for solids has to be defined. There exist three common types. The first is Martin’s diameter, which divides the particle into two equal parts. It depends on the orientation of the particle. Thus the average of some measurements, which are made in parallel, must be taken. The second is Feret’s diameter, where the maximum diameter from edge to edge is measured. And the last one is the projected area diameter, where the diameter of a circle, which has the same area as the particle, is taken.

For some application these definitions of diameters are anyways not sufficient and another parameter was introduced for clarification: The particle settling velocity. It means all particles with the same settling velocity are called equal sized, independent on their real shape.

Thus it is clear that it is of utmost importance to declare what kind of diameter is meant, because for every definition another value will be the result. However, not only the size of a single particle is of interest, but also the distribution of the sizes in an aerosol, because aerosols are seldom found with only one particle size. These are then called monodisperse. Normally aerosols contain lot of different dimensions and are therefore polydisperse. The experience(1) shows that under normal circumstances the log normal distribution fits best for the range of sizes occurring in the aerosol. This distribution is then described by the mean value and standard deviation.

As mentioned before aerosols are particles distributed in a gas. To describe now the behaviour of it, not only the particles are of importance, but also the behaviour of the gas. This fluid can be characterized by microscopic means as particles sized comparable to molecules. So the gas consists of small spheres which are moving randomly through the space. Therefore the statistical mechanics and the kinetic theory can be applied. A very important parameter is the mean free path of the gas molecules, which is the average distance a molecule can travel before it collides with another. The formula is derived by the virtual volume a molecule would sweep out if it would travel, the number of molecules (n) and the Maxwellian distribution of particles.

$$\lambda = \frac{1}{\sqrt{2} * n * \pi * \sigma^2} \tag{1}$$

σ…collision diameter [nm]

n...number of molecules []

λ...mean free path [nm]

To keep now the system of a gas molecule at steady state, forces act on it. The transfer of momentum, energy and mass are the most important parameters and they are represented by the viscosity, heat conductivity and the diffusion of a gas.

The other way to visualize the carrier gas would be the macroscopic way. Then the fluid or aerodynamics is of interest. The flow of the fluid can be generally subdivided into laminar in the vicinity of the pipe wall and turbulent areas in the middle of the flow stream. This flow regime is important to know, because most equations are only valid for one of these parts. The laminar flow regime can be detected in the near pipe wall region, while the fully turbulent part is in the middle of the pipe. If the medium is regarded to be incompressible and the gravitational forces are neglected, the only forces which remain acting on the fluid are the viscous forces and the inertia forces. The ratio of them is described by Reynolds.

$$\frac{inertia\_forces}{viscous\_forces} = \frac{\rho_m * \frac{v^2}{d}}{\mu * \frac{v}{d^2}} = \frac{\rho_m * v * d}{\mu} = \mathrm{Re} \tag{2}$$

ρ_m...density of the fluid [kg/m^3]

v... mean fluid velocity [m/s]

d...diameter [m]

μ...dynamic viscosity [Pas]

For low Reynolds numbers the flow would be called laminar, viscous or Stokes’s flow. In this region the viscous forces dominate and streamlines are derived. For fluids flowing in a pipe the upper limit of the Reynolds number would be around 2100. Above this the flow is intermediate, where both forces play a significant rule. This is valid for numbers up to 4000, while above the inertia forces are dominant. Then the flow is called turbulent and much mixing occurs in the flow.

Another significant factor for aerosol movement in a medium would be the resistance of the fluid to this motion. An often used parameter to describe this is the drag coefficient, which relates the drag force with the velocity of the body. Therefore the drag coefficient is directly dependent on the Reynolds number and for high values it becomes constant.

$$F_D = C_D * \rho * v^2 * d^2 * \frac{\pi}{8} \tag{3}$$

F_D...drag force [N]

C_D…drag coefficient []

v...velocity of the object relative to the fluid [m/s]

$C_D = \frac{24}{\mathrm{Re}}$ for laminar flow $C_D = 0.44$ for turb. flow

For the intermediate region many empirical formulas were derived.

In the laminar region now the resisting force changes because here forces, which act on the entire body, have to be taken into account. The first, who derived such an equation for the resisting force of the fluid, was Stokes.

$$F_D = 3 * \pi * \mu * v * d \tag{4}$$

d...diameter of the spherical particle [m]

v...particle velocity [m/s]

The assumptions, which are necessary to make this equation valid, are:

- incompressible medium
- infinite medium

- continuous medium
- rigid spherical particles
- viscous medium

At the first sight all these assumptions look very far from reality, but for some applications they are useful. The problem is that for flow in pipes at high pressures this equation will not be valid. Therefore additional turbulent terms are added.

2.3. Generation of aerosols

The production of gas can be out of a pure gas field or it can be delivered as associated gas of an oil field. In general the second type of gas is enriched with heavier hydrocarbons. Both gases must be treated after production to get rid of water and higher hydrocarbon components. The gas composition has to meet the requirements specified in Tab. 1 to be transported via pipelines

Regulations for gas composition and behaviour

	unit	EASEE-gas	DVGW G-260
Water dew point	°C, 70 bar	-8	Soil temp. at pipe line pressure
Condensate dew point	°C, <70 bar	-2	Soil temp. at pipe line pressure
max CO_2	Mol.-%	2.5	-
H_2S and COS	mg S/m3	5	4.7
Mercaptan	mg S/m3	6	6
Total sulphur content	mg S/m3	30	30
Oxygen	Mol.-%	0.01	3
relative density		0.555-0.7	0.55-0.75
Wobbe index	kWh/m3	13.76-15.81	12.8-15.7

Table 1: Regulations for gas composition and behaviour

These rules were made to avoid the generation of condensates, water and hydrates in the system. The gas is usually transported in international systems with a pressure between 35 and 80 bar. The pressure in the pipes is decreasing over its length. Therefore the volume of the gas is increasing and the velocity of the gas rises. Hence the gas has to be compressed at compressor stations to achieve a high enough pressure level for the transport.

Although these regulations exist, condensates, glycol and lubrication oil is sometimes found in the pipeline, which means that there must be generation circumstances in the line, which allow the formation of these liquids.

2.3.1. Retrograde gas condensation

The phase behaviour of natural gas is quite complex, because it does not consist of only a single component, but of chain of corresponding alkanes. For this reason the normal p-T diagrams, which is shown in fig. 1, changes, because the dewpoint and bubblepoint line shift and do not build a single line.

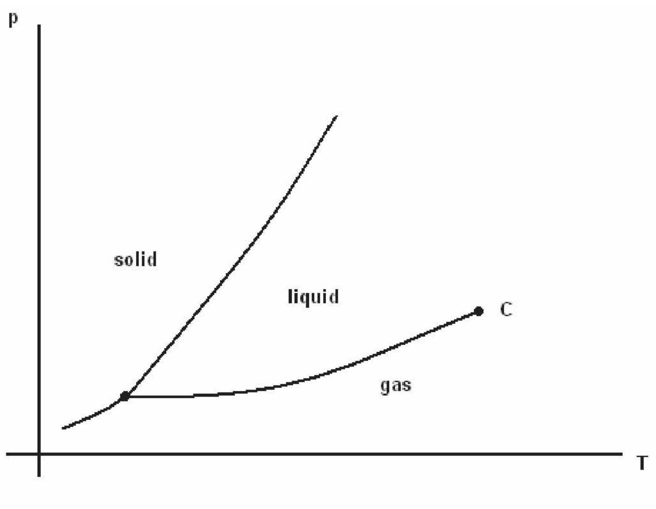

Figure 1: Single component p-T diagram

The fig. 2 shows a multiphase behaviour. Between the dew point and the bubble point line are the so called quality lines, which show constant liquid to gas ratios. Their origin is in the critical point. For single component substances this is the point above it is no longer possible to differ between liquid and gas phase. In the multi component diagram we can see that there exist mixtures of liquid and gas also above the critical point. The maximum pressure at which this happens is the cricondenbar and the maximum temperature is the cricondentherm. Therefore at the right side of the critical point inside the phase envelopes the retrograde gas condensation takes place. This means that by decreasing the pressure or increasing the temperature into the two phase region, liquid falls out of the gas as soon as the dew point line is crossed. This behaviour is the opposite to the properties of all other gases, which is a consequence of the non ideal behaviour of heavier hydrocarbons. Their solubility in methane is due to molecular interactions higher than ideal gas equations would predict it. For this reason alternative equations are taken

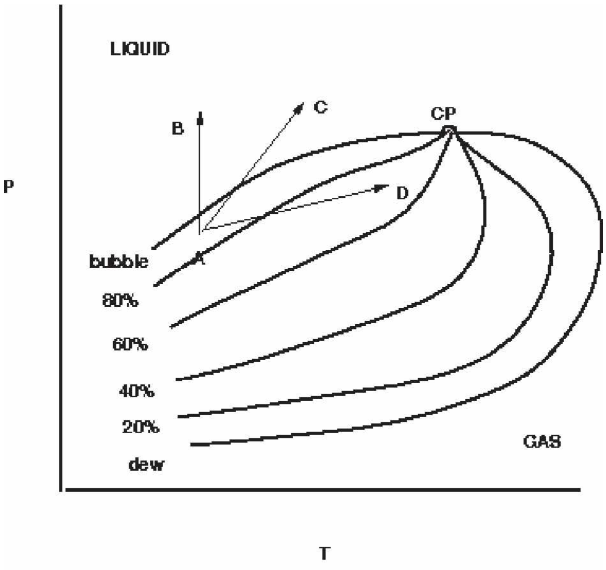

Figure 2: Multi component p-T diagram

For the forecast of the fluid behaviour several equations were setup in the past. The simplest form is the ideal gas equation.

$$p * V = n * R * T \tag{5}$$

p…pressure [bar]

V…volume [m^3]

n…number of moles [mol]

R…gas constant [m^3 bar/mol K]

T…temperature [K]

This calculation was improved by Van der Waals by introducing factors for the intermolecular attraction and repulsion forces and the volume of the molecules.

$$p = \frac{R * T}{V - b} - \frac{a}{V^2} \tag{6}$$

a...attraction parameter

b...average molecule volume

Although it makes quite better predictions on the fluid behaviour, it is not satisfying for practical applications. Thus further developments on this section were made by

Soave, Redlich and Kwong (SRK) or Peng and Robinson (PR), to mention only two of many. They made the phase behaviour also dependent on the eccentricity of the molecules, which can be large for heavy hydrocarbons.

Of further importance is the gas composition for determining the quality lines of the gas. A rich gas with high amounts of the ethane plus fraction has shifted its quality lines to the right side in comparison with a lean gas, which is only contaminated with compressor oil, although both gases show the same dew point line. This behaviour can be seen in fig. 3 and fig. 4.

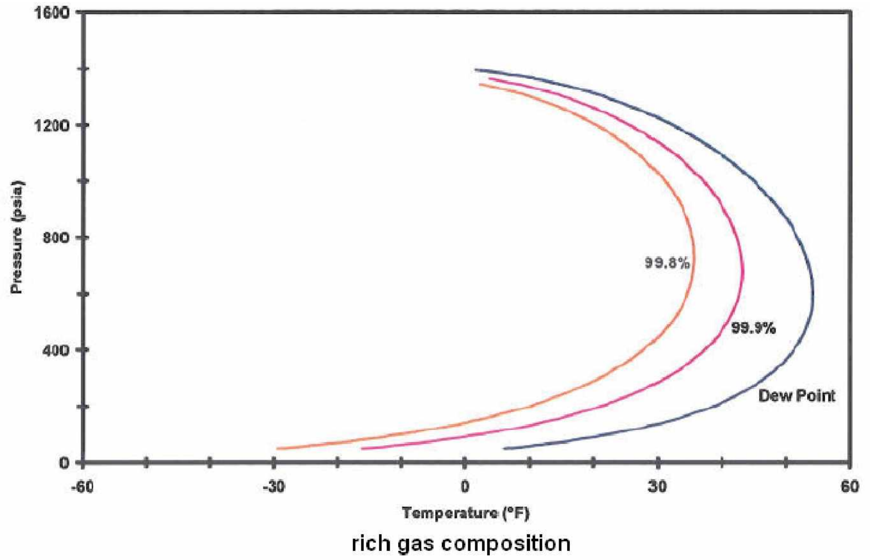

Figure 3: Quality lines rich gas composition (Dustmann et al.[36])

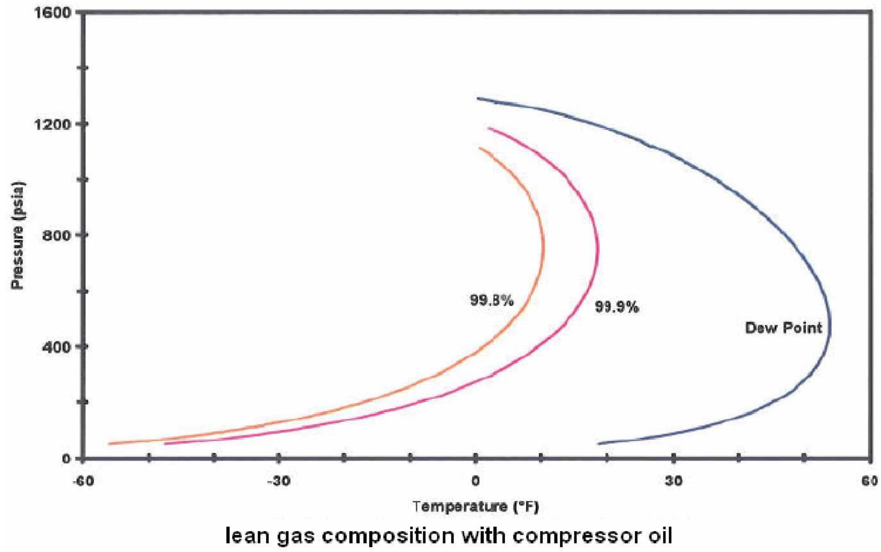

Figure 4: Quality lines lean gas composition with compressor oil (Dustmann et al.[36])

2.3.2. Effect of flow rate on condensation and evaporation

The movement of a droplet can be an influencing parameter for the evaporation of it, because during the motion at the front of the drop parts of it are taken with the surrounding gas stream. According to Parker C. Reist(1) in the lower Reynolds region is the accelerated evaporation balanced by the decrease of this rate at the back of the drop. For turbulent flow the situation changes. There the size of the particle is of utmost importance. Drops, which are larger than 40 µm, can react as if they are surrounded by vacuum. If the particles are smaller, then the relative movement between the gas stream and the drops is always in the low Reynolds region, because then the particles move nearly with the same velocity as the gas. This leads to the conclusion that the flow rate can be neglected only for small particles, while it increases the evaporation rate for larger particles, when the flow rate rises.

2.3.3. Joule Thomson effects

The Joule Thomson effect describes the temperature change of a gas in dependence of a pressure change. In most cases the temperature of the gas decreases with the reduction of the pressure and vice versa. Only when the initial conditions are below the inversion curve the temperature increases with pressure reduction. This inversion curve is dependent on the gas. Only in rare cases standard conditions are below the inversion curve. This would be the case for Helium.

The temperature change of the gas can be described by the Joule Thomson coefficient, which is substance dependent.

$$\mu_{J-T} = \left(\frac{\partial T}{\partial p}\right)_{H=const.} = \frac{V}{C_P} * (T * \alpha - 1) \qquad (7)$$

C_P…heat capacity at const. Pressure [J/molK]

α…thermal expansion coefficient [1/K]

H…enthalpy [Joule]

μ_{J-T}...Joule Thomson coefficient [°C/bar]

V...volume [m^3]

T...temperature [K]

It can be seen that the Joule Thomson coefficient is a function of the pressure and for ideal gases the coefficient is always zero and therefore no temperature changes occur. For real gases the coefficient is below the inversion curve positive and negative above. At one pressure two inversion temperatures exist as it is shown in the fig. 5.

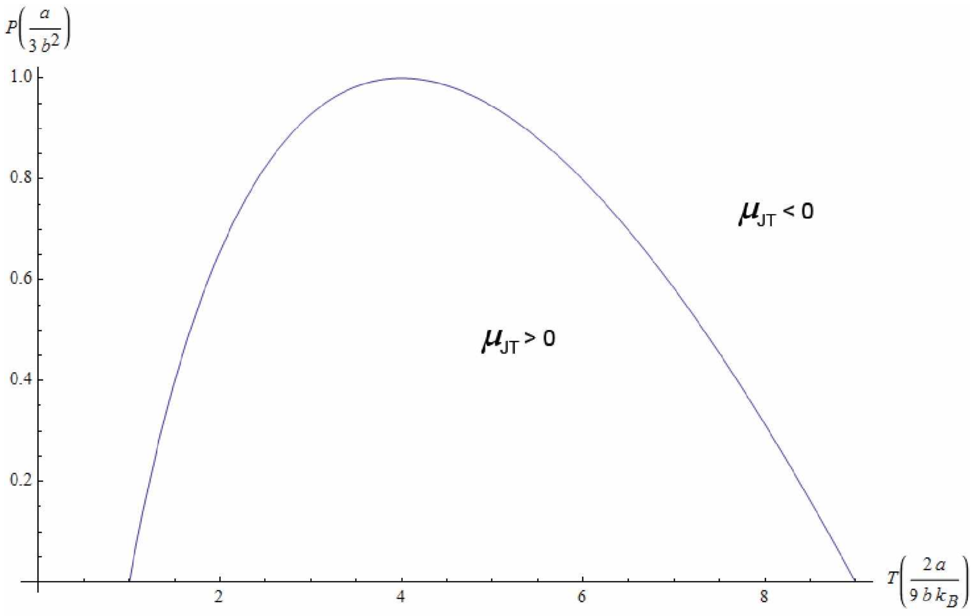

Figure 5: Joule Thomson inversion curve

For natural gas the maximum inversion pressure is between 600-700 bar dependent on the composition. If the composition of natural gas is simplified to consist only of methane, then the values of the Joule Thomson coefficient lies for 0-50 °C and a pressure between 40 and 80 bar between 0.5 °C/bar and 0.28 °C/bar as it is shown in figure 6. The temperature decrease caused by the Joule Thomson effect contributes to the generation of aerosols, because then the dew point temperature can be reached.

2.4. General transport mechanism of aerosols

The transport of aerosols depends on a large number of parameters, which can be subdivided into internal and external processes (Sager 2007):

Internal processes: 1) nucleation
2) condensation
3) coagulation

External processes: 1) convection
2) diffusion
3) thermophoresis

2.4.1. Nucleation

Generally nucleation is the development of small particles via change of phase. The necessary requirement is the saturation ratio of the carrier gas.

$$S = \frac{p}{p_S} \qquad (8)$$

p… partial pressure

p_S… saturated vapour pressure

It depends on the critical saturation ratio if a nucleus is built, or if only a cluster of molecules is formed, which has only a short lifetime. For homogenous nuclei growth, this means that the condensation takes place on the formed clusters of similar vapour molecules. The critical value for the saturation ratio is defined via the Kelvin's equation, which shows the dependency of the necessary diameter of a droplet for growth to the saturation ratio.

Due to this equation very high so called "super saturations" have to be achieved for small particle sizes, because only particles with a given size, which are built at saturations at the right side of the line, will grow, while others will evaporate again. The number of stabile clusters was defined by Pruppacher and Klett (2). Out of their lists it can be said that it needs at least 1 drop per cubic centimetre and second to reach spontaneous condensation. The size these aerosols achieve during this process is normally not the final one, because the particles will grow further due to coagulation.

The other case is the heterogeneous nucleation, where small solid particles build the condensation nuclei. Their size can range from some molecules up to a few microns; this is dependent on the source. These nuclei improve the condensation process in that way that smaller super saturation is necessary for stable liquid drops, but only a part of the existing nuclei are involved in the condensation process. How many particles are activated depend again on their size. So the largest nuclei are the mostly used and the smaller ones only start to react when the saturation is increasing. Generally we can further subdivide the nuclei into insoluble and into soluble ones. For the case of insoluble nuclei there exist two possibilities, whether it is wettable or not. If it is wettable the Kelvin equation can be used to predict the condensation behaviour, while for non-wettability the system reaches high complexity, because then only spheres are built on the surface of the particle. These spheres at some point form a coating and then normal condensation starts. The behaviour of this is dependent on the contact angle of the liquid. For soluble nuclei the critical saturation can decrease below one, but for the application in gas transporting systems they are not for interest.

2.4.2. Condensation

The growth and lifetime due to condensation and evaporation is also an important parameter, which influences the transport of aerosols in the gas stream. One equation, which describes these processes, is the Maxwell equation. The problem is that it includes many simplifications, therefore Langmuir improved it. For small particles further improvements were necessary for good predictions and these were done by Fuchs. With this equation it is theoretically possible to say how long a drop will exist after its condensation in relation to the surrounding saturation.

This equation shows that if the saturation of the surrounding area becomes one, then no further evaporation will take place. However the Kelvin equation tells that this can’t be the truth. Due to Parker C. Reist(1) small droplets will further evaporate because of curvature effects and the interfacial tension difference also when the media is already saturated.

2.4.3. Coagulation

As mentioned earlier the dimension of the particle can change due to coagulation. This is dependent on the Brownian movement of the particles, on to gravitational forces or turbulence. All these forces lead to velocity differences between the particles, which are reasonable for the collisions and coalescence of the particles.

The coagulation leads to larger particle sizes, but can not change the overall mass. Thus the concentration of particles distributed in the gas must decrease. To predict resulting size distributions numerical models, which predict the dimensions over time, have to be used. There are also analytical analyses for this approach, which are representative for the distributions, but not exact. The principle mechanisms of agglomeration can be classified into (Ho Chi Ahn(37)):

- **Thermal agglomeration:** The difference in temperature in a fluid induces a stochastic movement of the particles, which is called Brownian movement. When the gradient is high the movement increases and the probability that the particles collide is growing. Therefore more agglomeration occurs.
- **Agglomeration through shear strain:** Particles in a stream whether laminar or turbulent can have different velocities due to this current. This lead to collisions and coagulation, but it only important for particles above one micron.
- **Turbulent agglomeration:** Due to the turbulent behaviour of the carrier gas the particles are accelerated or decelerated. Thus there are again different velocities of the particles which lead to collisions of them.
- **Electrostatic agglomeration:** If an electrical field influences the particles, their velocities will change due to different possible chargeability. This will lead to agglomerations.
- **Acoustic agglomeration:** Acoustic waves can undulate the particles, which make it possible at amplitude maxima that the particles path intersect and they collide.

- **Agglomeration through other influences:** The coagulation of particles can be also an effect of the gravitation or centrifugal forces. These forces are changing the velocities of the particles in dependence of their size and hence lead to collisions and formation of other size distributions.

The particle size distribution, which follows from these mechanisms, can be described by a formula of Smoluchowski . It describes the change in particle density over time:

$$\frac{\partial n(v,t)}{\partial t} = \frac{1}{2} * \int_0^v K(v', v-v') * n(v',t) * n(v-v',t) * dv' - n(v,t) * \int_0^\infty K(v,v') * n(v',t) * dv'$$

K(v,v’)… agglomeration frequency function: describes, how much of the particles collide and stick together afterwards

n(v,t)… density of particles in a definite volume at a given time

The first part of the right side of the equation is the production rate of particles with the volume of v due to collision of particles with the size of v’ and v-v’. The other one describes the decrease rate of particles, which are lost due to accumulation of particles with the size v. Therefore this equation is only analytically solvable, when K(v,v’) is developed correctly for each particle size, the conglomeration of the aerosols is irreversible and when the particles have spherical shape. Furthermore only binary collisions are counted and each collision leads to adherence of the particles.

To derive the equation for the agglomeration frequency the collision rate (N_{ij}), the reduction of the strike probability (n_{ij}) due to fluid mechanics and the adherence probability (H_{ij}) are taken into account.

$$K_{ij} = N_{ij} \times \eta_{ij} \times H_{ij} \qquad (9)$$

These parameters are characteristic for the transporting mechanisms with the fluid dynamic relations and the physical and chemical interactions of the particles.

The collision rate was firstly described over the whole Stokes particle number area in the 1996 by Kruis and Kuster. They developed an equation, which shows the changes of it due to variation of particle size and turbulence criteria.

$$N_{ij} = \sqrt{\frac{8 * \pi}{3}} * (r_{pi} + r_{pj})^2 * \sqrt{(u_{rel1}^2 + u_{rel2}^2)} \quad (10)$$

u_{rel1}…relative particle velocity due to inertial turbulent effects

u_{rel2}... relative particle velocity due to shear turbulent effects

Out of this equation the forces, which are acting on the particles, while they are coagulating. With increasing turbulence the Brownian influence decreases, while other forces rise. The fig. 6 shows the collision rate dependent on particle size and turbulence.

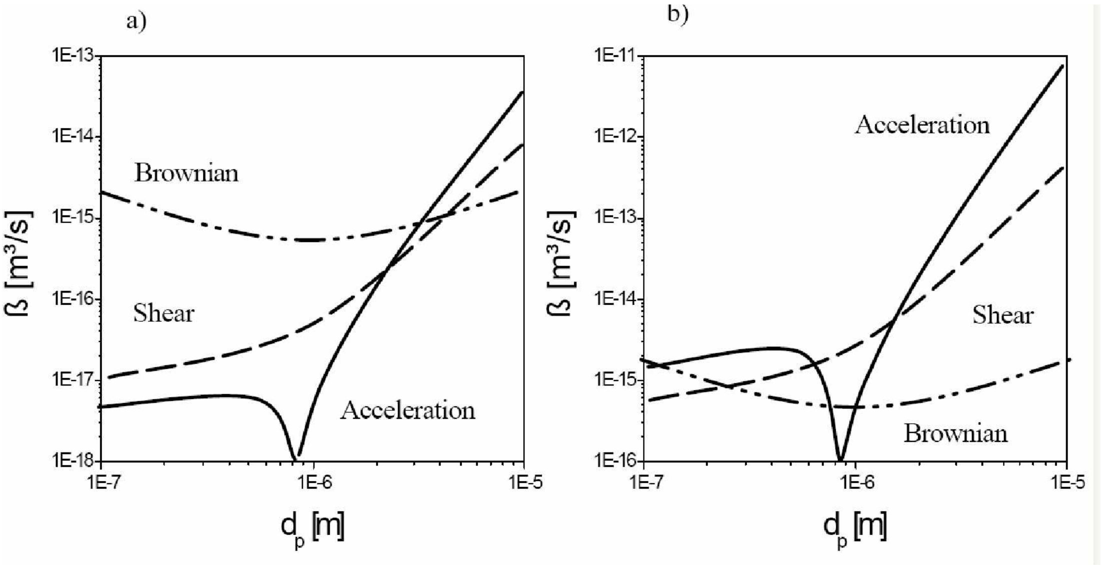

Figure 6: Collision rate dependent on particle size and turbulence[37]

Figure a) shows the mechanisms for v_f =0.1 m/s and ε=5*10^{-4} m^2/s^3, while figure b) is a plot for v_f =1 m/s and ε=1 m^2/s$^{3.}$

The strike probability for turbulent flows is difficult to measure, thus the evaluations of different authors are only based on numerical calculations. Another name of this probability is often also collision efficiency. Pinsky [(38)] solved this problem with two lateral distances to find the collision cross section, which is according to them not formed as a circle. This leaded to a higher probability of collision for turbulent flow than from laminar one.

To solve the equation for particle density over time several analytical methods were developed, which make assumption far away from real conditions in gas transporting systems. Therefore the only possibility to solve it would be a numerical one. It is highly probable that the coagulation of the aerosol particles in the system do not play an important role.

2.4.4. Convection

The convection, which is for interest in the flow through pipes, is the enforced, where the stream is induced through compression of the gas. At the beginning of the flow through pipes the final flow regime is normally not directly reached, but for the long distances, which the gas flows in the transition pipelines, a fully developed pipe flow profile can be expected. This means that in the middle of the pipe a turbulent flow is generated, while at the sidewalls a boundary layer with laminar flow can be recognized. The width of this layer can be evaluated (Schmidt 2001(4)) with:

$$\delta_V = \frac{25.14}{\mathrm{Re}^{\frac{7}{8}}} * d \tag{11}$$

δ_V ...layer width [m]

d…pipe diameter [m]

Re...Reynolds number []

With increasing Reynolds number and decreasing pipe diameter the thickness of this layer is reducing. Because of the high amount of gas, which is transported through the TAG, we have to assume that the flow in the pipe is highly turbulent. This has a high impact on the particle transportation behaviour and on the friction pressure losses during the transport. These losses are normally described by several models, which will be discussed in a later part of this thesis.

2.4.5. Diffusion

According to Sager 2007(6) small particles like aerosols have impulse exchange with the surrounding gas and other particles. This leads to a stochastic movement of aerosol, which is not directed. It is called Brown's particle movement following the name of Brown's molecule motion.

The other possibility, why diffusion can happen, is that there is a difference in the concentration of a substance. The resulting movement (j_P) can be described via Fick's first law about material flow density.

$$\vec{j}_p = -D_p * \nabla c_p \qquad (12)$$

D_p…diffusion coefficient

c_p…concentration

The diffusion coefficient is normally dependent on the Boltzmann constant, the friction factor and the mean temperature. When the temperature is increasing and the size of the particles is decreasing, then the diffusion coefficient becomes larger. The diffusion itself is mostly relevant for laminar flow regimes except turbulent diffusion is meant.

For this case the turbulence will support the natural diffusion, because the turbulent core of the pipe current adds supplemental mixing and minimizes the concentration differences. Therefore the maximum diffusion will be between the laminar boundary layer and the core. This leads to increased particle movement to the sidewalls and hence to more particle deposition. This movement is quite complex and there exist several mathematical solution, which are only useable in small ranges. One complex calculation, which take into account also gravity and pipe surface roughness is that from Fan and Ahmadi (1993).

The gravity can influence the system only for particles, which are bigger than 1 µm, because for smaller particles the force becomes negligible due to the reason that the ratio of the Brown movement to the gravity becomes very small. An important thing is the flow direction for this kind of segregation, because in some cases the gravity is supporting the deposition, while in others it can be neglected.

If only the gravity and the resisting force from the fluid to the particle is taken into account, an equation for the terminal settling velocity could be found.

$$v_d = \frac{C_S * \rho_p * g * d_p^2}{18 * \eta} \qquad (13)$$

C_S…Cunningham slip correction (for particles at the size of the mean free path)

ρ_p…density of the particle

g…gravity

d_p…diameter

η…dynamic viscosity

2.4.6. Interception and impaction of particles

The interception of particles is caused by the movement of a particle in the proximity of a wall. The settling is due to the fact that particles do have some size and the critical distance for interception is the half of the particle diameter. Out of this we can see that it is quite an inefficient method for particle separation.

A more important effect is the impaction of particles. Due to the inertia, aerosols can not follow changes in velocity or direction of the stream immediately. Therefore they are moving a short way in the original direction of the flow. A parameter to describe the effect of inertia analytically is the particle relaxation time, which is the characteristic period a particle needs to change its velocity to at least 63 % of the new one, which means it reaches equilibrium conditions (Sager(6) 2007).

$$\tau_p = \frac{\rho_p * d_p^2 * C_S}{18 * \eta} \text{ … particle relaxation time} \qquad (14)$$

ρ_p ...particle density

d_P...particle diameter

C_S…Cunningham slip correction

η ...viscosity

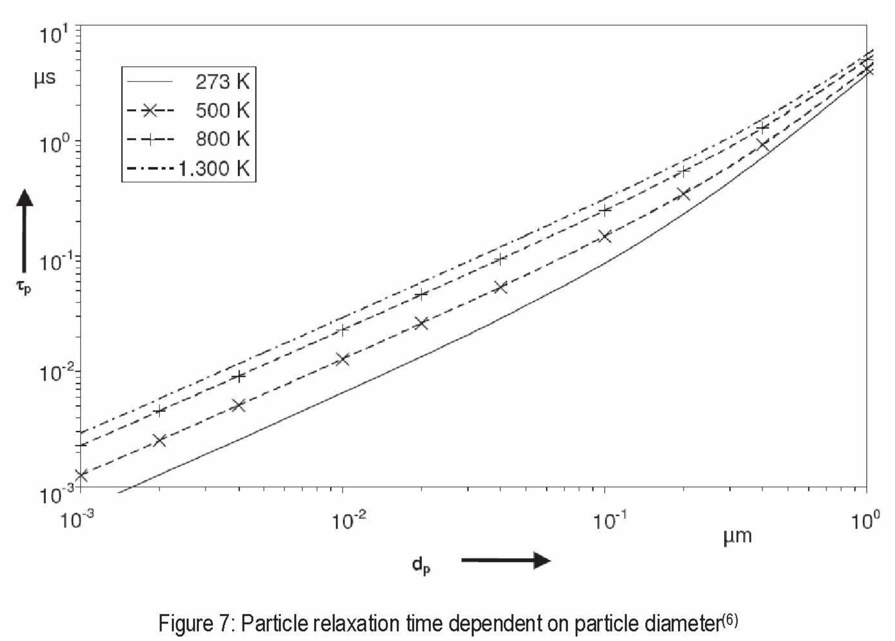

Figure 7: Particle relaxation time dependent on particle diameter(6)

Naturally the phenomenon of inertia is for larger particles more important than for smaller ones as it can be seen in fig. 7. Out of this time it is possible to determine the distance, which the aerosol can travel in the meanwhile, which is called the particle stop distance (Friedlander 1977(7)):

$$S = \frac{\rho_p * d_p^2 * C_S}{18 * \eta} * v \text{ ...molecular mean free path} \qquad (15)$$

v…fluid velocity

ρ_p ...particle density

d_P...particle diameter

C_S…Cunningham slip correction

η ...viscosity

This is then the path an aerosol can move in the old direction before it changes its way to the new one. Thus it can be said, this is the distance a particle must be away from the wall, so it is able to stay in the gas stream.

Eminently important is the impaction of particles in tube arches. Also for this effect many people developed different models. One simple model is a two dimensional one from Crane and Evans(32). They said that the separation rate is only dependent on the bow angle (φ) and on the Stokes number (Stk):

$$D = \frac{Stk * \varphi}{2} \tag{16}$$

$$Stk = \frac{\rho_p * d_p^2 * v}{18 * \eta * \frac{d}{2}} \tag{17}$$

d...pipe diameter

Therefore it would be satisfactory to know the geometry of the bow and the fluid parameters, and then it is possible to calculate the separation in a bow. The problem with this idea is that normally monodisperse particles do not occur in nature. Thus for every size a different separation rate exists.

2.4.7. Thermophoresis

If the temperature in a pipe is not homogenous, but has a certain distribution, then this acts as a force on the aerosol particles in the direction of the lower temperature. This phenomenon is called thermophoresis. There exist two possible explanations for this effect. Smaller particles, which are already in the sub-micron region, collide more often with the surrounding gas molecules, when they are hot, because then the relative movement of the gas molecules is faster. Therefore the particles are pushed in colder regions. For larger particles exists a second explanation. This means that due to the temperature gradient gas starts to flow in a microscopically stream over the single particles and this drifts the particles to the colder side. Most of the models, which were developed for the separation of aerosols, can only predict correct values for a laminar flow regime, but a simple form for calculation in the turbulent region is that from Sager(6) (2007):

$$D = 1 - \left(\frac{T_W}{T_e} \right)^{\Pr^* K_{th}} \qquad (18)$$

D...separation rate

T_e…entrance temperature of the fluid

T_W…wall temperature

Pr...Prandtl number

$$K_{th} = \frac{2.294 * \left(\frac{\lambda_g}{\lambda_p} + 2{,}2 * Kn \right) * C_S}{(1 + 3.438 * Kn) * \left(1 + 2 * \frac{\lambda_g}{\lambda_p} + 4.4 * Kn \right)} \text{ ... thermoph. Coefficient} \qquad (19)$$

λ_g, λ_W…thermal conductivity parameters of the gas and the wall

$$Kn = \frac{2 * \lambda}{d} \text{ ...Knudsen number}$$

(20)

λ…mean free path

d...characteristic length of the flow

This model enables the prediction of deposition due to thermophoresis. The problem with this calculation is that the aerosols are normally not monodispersed, but have a broad range of sizes. Therefore the evaluation must be done for the mean value of the distribution.

2.4.8. Combination of different mechanisms

In a complex situation like in the transport of natural gas, where many factors are influencing the generation and transmission of aerosols it is clear that not only one of the above mentioned mechanisms is acting. Instead of that a combination of all is creating the parameters for sedimentation and transport of liquid plugs in the pipes. Therefore two different approaches exist, which try to balance several of these effects. The first is the mathematical one, which do no take the physical realities into account. Therefore the prediction is often wrong, because some effects are supplying each other, which leads to higher accumulation rates. The problem with both approaches is that only few different aspects can be taken into account, if it should stay analytically soluble.

2.5. Settling of aerosols in tubes and pipes

2.5.1. Ordinary flow regimes in pipes for two phases

The flow in pipes is a highly researched topic for the oil and gas industry. In the last years many models were developed to predict not only the flow regime in horizontal and vertical pipes, but also for all deviations in between. In general we can differ between the empirical models, which are often used due to their simplicity. For these models normally no simulation is necessary and first assumptions on the pressure draw down and the flow regime can be made. The other models are the mechanistic models, which are complicated and difficult to handle. Today's research is at this region.

In general the flow in horizontal pipes is normally diverted into stratified, slug and dispersed flow dependent on the amount of gas and liquid, which is transported in the pipe. For these flow patterns often maps are developed, which allow the prediction of the flow. The problem with these maps is that nearly all of them were calculated on the basis of high liquid amounts in the flow. Therefore the maps are only extrapolated for the region of dispersed flow and hence not accurate for the prediction in transmission pipelines, where the gas includes only small amounts of liquid. Hope et al(8) showed this in their study, because they compared several single phase models with two phase models for the pressure drop prediction of North Sea pipeline with a small amount of liquid. They found out that the single phase models give for this situation the better results.

Generally the flow pattern is dependent on the phase densities, viscosities, velocities, surface tension and the gas liquid ratio. One of the best known maps is that of Mandhane, which can be easily read in fig. 8. The several flow regimes, which can be found in the map are displayed in fig. 9.

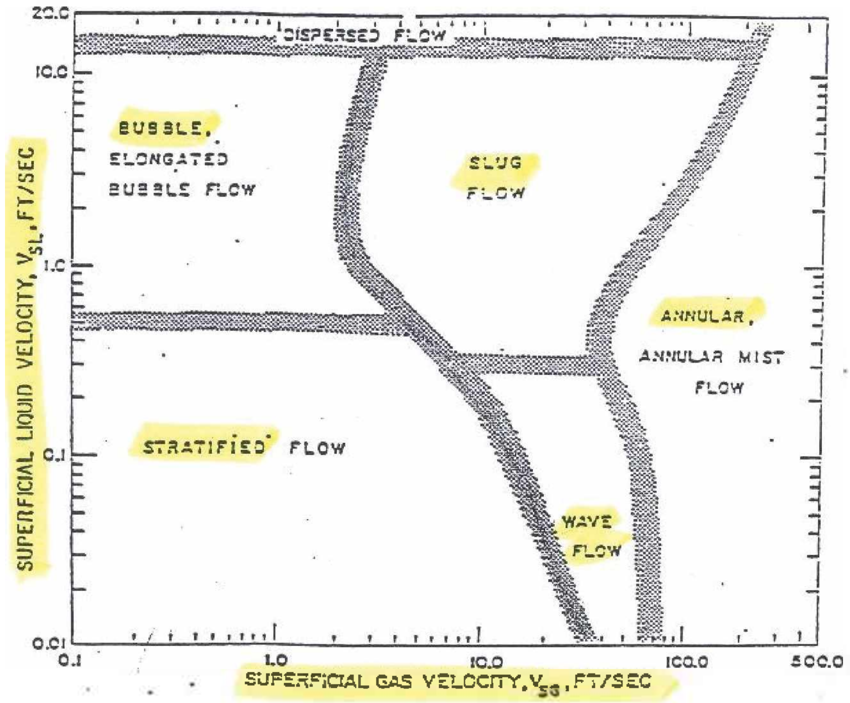

Figure 8: Flow pattern map after Mandhane[39]

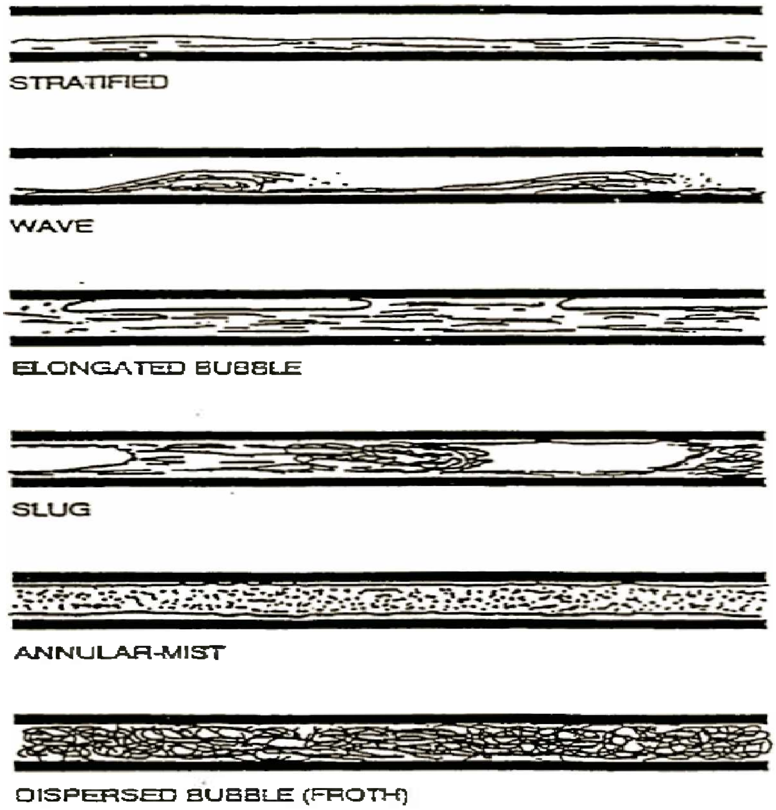

Figure 9: Flow patterns after Mandhane[39]

Two phase empirical models:

They can be subdivided into three classes with increasing precision:

- No slip, no flow pattern model: These ones are the oldest theories, which were developed in the fifties and sixties of the 20th century, and they are normally not in use any longer. These models don't consider the liquid hold up in the density and the friction factor.
- No flow pattern model: The different velocities of oil and gas are taken into consideration to predict the liquid hold up and the friction factor along the pipe. An important model in this category is the Hagedorn and Brown correlation.
- Slip and flow pattern are taken into consideration: These types of calculation are still in use to evaluate the flow regime and pressure losses along pipelines. The most important representatives are Duns and Ros, Orkiszewski and Beggs and Brill. Some of the newer models can be only calculated on the computer.

Duns and Ros correlation: It was developed for the flow of oil and gas in vertical pipes. Therefore it starts over predicting the pressure losses, when the pipe is smaller than three inch, when the oil gravity is above 56 or below 13° API, when water is in the fluid stream and for gas liquid ratios above 5000. Duns and Ros evolved a map with three different flow regimes with transition zones in between. This map was based on two dimensionless numbers: The liquid velocity number and the gas velocity number, which include the superficial gas and liquid velocity, the surface tension and the density of the liquid. Due to the fact that this correlation has many restrictions, it is not very common any longer.

Orkiszewski correlation: This model was not a new calculation for the flow regime, but he said that the existing methods do not predict the flow sufficient for all occurring sections. Therefore he chose different models for several regions. The resulting flow pattern map is shown in fig. 10.

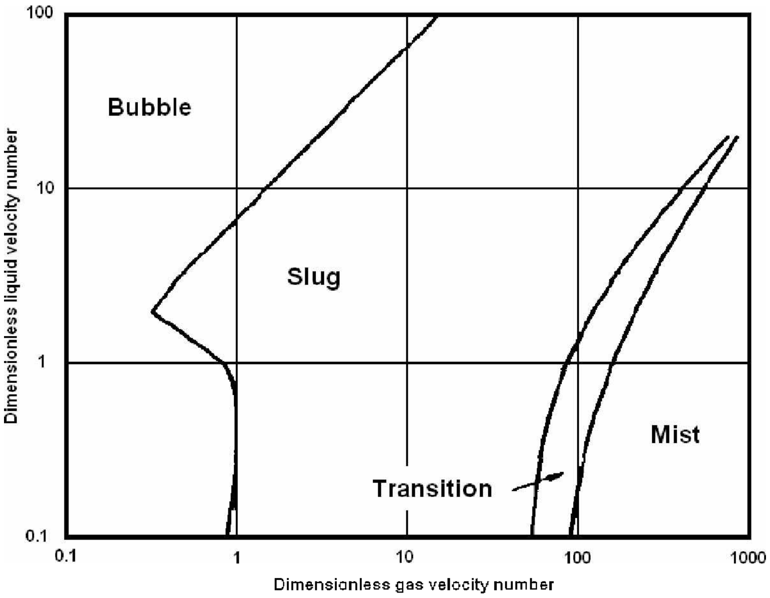

Figure 10: Orkiszewski flow pattern map[40]

Method	Flow Regime
Griffith	bubble
Griffith and Wallis	slug (density term)
Orkiszewski	slug (friction term)
Duns and Ros	transition
Duns and Ros	annular mist

His assumptions are also only valid for vertical pipe flow. It can be applied on small tubings below two inches with oil, gas and water flowing below gas liquid ratios of 5000.

Beggs and Brill: This scheme was originally developed for the flow in horizontal pipes, but is applicable to all inclinations. Due to its good results it is often used as basis for mechanistic models. They also evolved a map with different flow regimes:

Segregated: stratified, wavy and annular flow [($\lambda_l<0.01$ and $N_{Fr}\leq L_1$) or ($\lambda_l\leq 0.01$ and $N_{Fr}<L_2$)]

Transitional: ($\lambda_l\geq 0.01$ and $L_2<N_{Fr}<L_3$)

Intermittent: plug and slug flow [($0.01 \le \lambda_l < 0,4$ and $L_3 < N_{Fr} \le L_1$) or ($\lambda_l \ge 0.4$ and $L_3 < N_{Fr} \le L_4$)]

Distributed: bubble and mist flow [($\lambda_l < 0.4$ and $N_{Fr} \ge L_1$) or ($\lambda_l \ge 0.4$ and $N_{Fr} > L_4$)]

With increasing velocity of the fluids the flow pattern is changing from segregated to distributed, where one phase moves as mist in the other. This is the flow regime, which is important for the aerosol transport. The formula, which are written below, are necessary for the evaluation of the characteristic numbers.

$$N_{Fr}^2 = \frac{u_m^2}{g * D_p} \qquad \lambda_l = \frac{u_{sl}}{u_m} \qquad L_1 = 316 * \lambda_l^{0.302}$$

$$L_2 = 0.0009252 * \lambda_l^{-2.46847} \qquad L_3 = 0,1 * \lambda_l^{-1.4516} \qquad L_4 = 0,5 * \lambda_l^{-6.738}$$

$$u_m = u_{sl} + u_{sg} \qquad u_{sl} = \frac{q_l}{A_p} \qquad u_{sg} = \frac{q_g}{A_p}$$

N_{Fr}...Froude number

u_{sl}, u_m, u_{sg}...fluid velocities

L_1, L_2, L_3, L_4...characteristic numbers

Asante (2000): This model, which he developed, is especially made for gas transmission lines, which transport only small amounts of fluids. This gas normally called dry gas can transport liquids like lubrication oil, glycol and gas condensates but not more than 10 bbl/MMSCF. Therefore only two flow regimes are possible: The dispersed flow and the stratified flow. To account for these regimes the model is divided in two sections to describe the transport of the fluids. The first is a homogenous approach, which is taken, when the flow is dispersed and the second is a two phase stratified approach, when the flow changes to the segregated regime.

The decision, which flow is the correct one in the pipe, is based on the calculated liquid hold up and then compared to the numbers of the decision tree displayed in fig. 11.

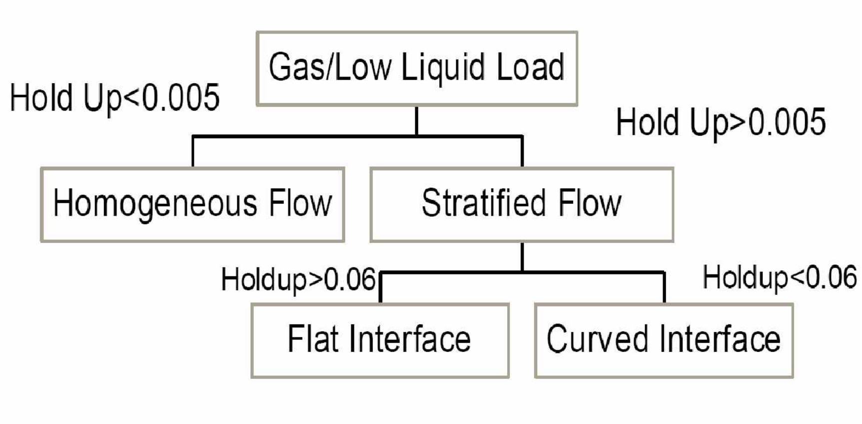

Figure 11: Decision tree for flow pattern [9]

The homogenous flow means that the liquid is dispersed in the dominant gas phase. To calculate the liquid hold up in the pipe an older model is used. It is the Hart and Hammersma correlation of 1987. They defined a formula based on the liquid Reynolds's number, on the superficial gas and liquid velocity and on the densities of the fluids, where ε_L is the liquid hold up.

$$\frac{\varepsilon_L}{1-\varepsilon_L} = \frac{u_{SL}}{u_{SG}} * \left\{ 1 + 10,4 * \mathrm{Re}_{SL}^{-0,363} * \left(\frac{\rho_L}{\rho_G} \right)^{0,5} \right\} \qquad (21)$$

u_{SL},u_{SG}...superficial velocities

Re_{SL}...Reynolds number

ρ_L , ρ_G ...fluid densities

On the basis of this formula the flow regime can be decided and that the pressure drop along the pipeline can be calculated.

The important aspects of the formula are the velocities, which are dependent on the amount of gas and liquid and the pipe diameter. Therefore to predict the correct flow regime in the pipe it is necessary to estimate as accurate as possible how much liquid is transported with the gas. For this reason a worst, a best and a most likely scenario are evaluated in the later section of this thesis. The other important parameters are the densities for the liquid and the gas beside the viscosity of the fluid, which have to be evaluated.

2.5.2. Pressure Losses in pipe flow

The overall pressure losses in a pipe can be described by the following equation:

$$\Delta p = \Delta p_{PE} + \Delta p_{KE} + \Delta p_{F} \qquad (22)$$

Δp_{PE}...pressure drop due to potential energy change

Δp_{KE}…pressure drop due to change of the kinetic energy

Δp_{F}…pressure drop due to friction

If the momentum and the continuity equation are put together and inserted into the above mentioned equation, then the calculation below can be used. The problem is that this has some limitations. The assumptions are:

- steady state flow
- no compressors in the system
- adiabatic behaviour

$$\frac{dp}{dl} = \rho * g * \sin\theta + \rho * v * \frac{dv}{dl} + \frac{f * \rho * v^2}{2 * d} \qquad (23)$$

ρ ...density of the fluid

g...gravity constant

θ ...inclination

v...fluid velocity

d...pipe diameter

f...friction factor

The equation 23 gives a prediction of the total pressure losses of a fluid of a pipe flow. The first term describes the elevation or change in potential energy, the second pictures the losses due to acceleration or the change of kinetic energy, while the last one characterizes the pressure losses because of friction.

A rule of thumb is that for vertical flow the first term makes about 70-90% of the overall pressure drop, the second only 0-10% while the last one contributes from 10-30%. This changes dramatically, when the flow becomes horizontal. Then the first term is negligible, while the last one contains nearly 100% of all pressure losses in the pipeline. Therefore it is necessary to keep the velocity as low as possible in horizontal pipes and determine the friction factor exactly.

An important issue for the prediction of the pressure drop is the correct calculation of the friction factor. The problem with this determination is that there are two possibilities of turbulent flow. One is the partially rough flow, which is dependent on the Reynolds's number and happens for intermediate flow rates. The other is fully rough flow, where pipe roughness is the determining parameter for the flow regime. The models with the most accurate evaluation are the Colebrook White and the AGA equations. The first is the more conservative one, which predicts pressure drops with a single equation for the flow regime, while the AGA model is based on two different equations. Uhl (1965) found out that for gas transmission lines AGA predicted the pressure draw down best.

Because of the above mentioned limitations of this equation normally half empiric models like Beggs and Brill are taken. This is a model that assumes homogenous flow. This means that the gas and the liquid phase are treated as a pseudo single phase and everything is calculated with mixture parameters. If a stratified flow approach is taken everything becomes more complicated, because than not only the mixture friction factor has to be calculated, but there must be an evaluation for the gas to wall friction and for the interfacial friction factor. An example for this model would be the correlation of Duns and Ros, but also the above mentioned theory of Ben Asante can be taken for the prediction. In this case it should be the most ideal one, because it is developed for low liquid loads.

2.5.3. Temperature Distribution in a pipeline system

The temperature distribution of the natural gas flowing in a system is important for the prediction of the liquid drop out points. The highest temperature can be found after the compressors due to the heat, which is produced with the compression of the natural gas. Afterwards the gas is cooled down by large air coolers before it flows into the transmission pipe. In the section after the compressor stations there is a rapid decrease of temperature due to a high temperature gradient between the gas and the surrounding area.

The friction between the wall and the gas contributes also to the decrease of temperature. Furthermore the forces, which act between the liquids in the gas and the gas itself, are changing the temperature of the gas. This means that the drag between the fluids and gas reduce the temperature and the latent heat due to condensation and vaporization causes also changes.

Another influencing parameter is the undulation of a hilly terrain. During upwards movement the gas starts to cool down and in the downwards phase the temperature increases again. This phenomenon can be explained by the fact that during upwards movement the gas must act against gravity, while in the downward phase, things turn round.

2.5.4. Aerosol accumulation

Accumulation in turbulent pipe flow:

According to Sager(6) (2007) the accumulation and segregation of aerosols from a gas stream depends on several parameters. Although his study was done for small diameter pipes, it is also applicable for larger diameters, because he found out that the deposition is independent from the pipe diameter, when the Reynolds number is the same.

One of his conclusions is that for aerosol accumulation the particles must be subdivided into submicron and supermicron, which means smaller or larger than 1 µm, because of the different segregation behaviour of these particles. The submicron particles are easier segregated in large diameter pipes, while it depends on many influencing factors for supermicron aerosols. One thing, which should be considered, is, if the pipes are horizontal or vertical. When they are horizontal than small pipe diameters are ideal for separating aerosols.

When the gas stream is cooled down rapidly, then the deposition velocity increases rapidly. This is the case when the pressure is decreased at branching stations due to Joule Thomson effect. A slower cooling down of the gas happens during the transport after the compressors or when the gas is transported above the ground the ambient temperature is reducing the flowing temperature of the gas.

Another factor, which influences the deposition of aerosols, is the geometry of the flowing path of the gas. The larger the diameter of the pipe, the easier the particles can travel with the fluid stream and the fewer are separated. When the turbulence of the fluid stream increases, which means that the velocity of the gas goes up, then the also smaller sized particles, on which the inertia forces don't act as strong as on larger ones, are separated in the elbows. Moreover the smaller the radius of the bow and the more the curvature comes close to 90°, the larger is the mass of particles, which will be segregated in the elbow. An crucial hint for this separation is, that if a particle draws nearer to the wall than half of its diameter, then it will be deposited.

One principle force, which also acts on particles, is the gravitation, which supports the settling of the aerosols at the bottom of the pipe.

The problem for defining how long the particles can be transported in the fluid stream is that due to condensation the size of the aerosols change.

Accumulation of aerosols at expansion places:

At places where the pressure is decreased rapidly like it is often at branching points, the transport of aerosols is changed. According to Ahmadi et al.(5) the following facts have to be taken into consideration:

- particles with Stk>1 follow the gas downstream
- deposition of particles at the expansion place increases with rising Stokes number
- the majority of the submicron particles is deposited at the expansion point due to recirculation phenomena
- large particles predominantly are transported further
- lift force and gravity are negligible

2.5.5. Fluid path at branches

Gas liquid mixtures partly undergo a separation at branches and junctions in a pipeline system. This leads to different compositions before and after such connections. One stream is liquid rich, while the other becomes "drier". Baker et al.(5)

made experiments about this division with two T-branches in connection find the optimum segregation constellation for these junctions. The flow pattern they used where in the region of stratified wavy flow and annular mist, which is quite the same as expected in the transmission line, when fluid drops out and has time for some accumulation, and also slug flow, which can happen downhill. This flow pattern is crucial for the separation that takes place and also the gas split ratio is critical, because when more gas flows into the branch the velocity of the gas in the branch increases and also the frictional pressure goes up. Therefore a pressure drop at the inlet is generated and this sucks more liquid into the junction.

Furthermore the flow rate is important for the split of the liquid into the branch, because for lower flow rates the forces of inertia act less on the fluid. Therefore it is easier for it to slide into the branch and higher liquid in the bypass is the output. For these low flow rates a so called “Flip-flop” effect (Martinez et al.) must be taken into account. This means that only a part of the gas, how much this depends on the flow rate, is sucked into the branch, while the total amount of the liquid flows into the branch. If the amount of gas that goes into the junction is too small, then the whole fluid will run into the main path.

For disperse flows the segregation of the fluid and the gas is at a T-junction, where both arms have the same diameter, equal. This means the more gas is flowing in the branch the more fluid goes in there. If the diameters are different, than only for dispersed flow the segregation of the fluid stays proportional to the split of the gas stream. For all other flow regimes a reduced diameter of the branch means a decreased liquid stream into the junction. This is due to the fact that the branch is normally not at the bottom or the pipe, but in the centre mounted. Therefore the liquid has to move up when it enters the side arm.

When the splitting at the branch is unequal, like it is normally for annular and stratified flow, then the overall phase diagram also changes. The original phase diagram of the gas is shifted to the right side for the arm with the higher liquid amount and vice versa. This behaviour can be seen in fig. 12.

The conclusion is that only by knowing the flow pattern at the tee, it can be said which path the liquid will approximately go.

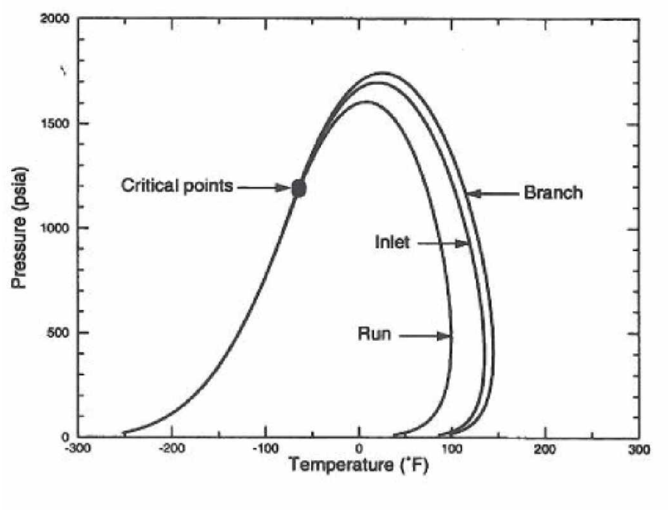

Figure 12: Phase envelope shift[5]

Therefore the conclusion has to be that branching arms are only significant for the system, when the liquid amount is high enough to leave the dispersed flow regime and builds up a liquid film. Then the combination of more T-junctions becomes important. This phenomenon is already used for phase separation in a petrochemical plant in the United Kingdom (Baker et al.(5)). However, for this use not only the optimum combination, but also the correct geometry is of importance. Thus two on the opposite sides of pipe mounted tees can produce one stream without any gas and another with only 10% liquid left and this over a wide spectrum of inlet conditions. Other possibilities to get rid off the liquid are the downward installation of a branch with a liquid level control valve or without one, which would act as a constant liquid reducer.

2.6. Removal of aerosols

2.6.1. Filter technology

The problem of liquids in the natural gas transmission system is well known. The sources are the drying processes, some corrosion, spray effects on flow restrictions and also the two phase flow of gas. The size of the particles built very significantly:

condensation aerosols: 0.1 – 5 µm

aerosols produced by flow restrictions: 9 – 200 µm

aerosols from liquid entrainment: 400 – 3000 µm

Although the amounts of liquid are normally in a dry gas transmission system very low, some separators are usually installed along the pipeline. The use of these separators is dependent on the size of the droplets, because most are not built for small aerosols.

The separators rely on different segregation mechanisms and consist of several parts, which use them. These mechanisms are the gravitational force, when it overcomes the drag force of the gas stream, the centrifugal force, which can be higher than the gravitational force, the impaction of particles and the Brownian motion of the droplets. These forces are sorted due to their dependence on particle size.

Primary separation:

The gas enters a separator and flows directly against a deflector plate or into a cyclone were the velocity of the free fluid is reduced and it drops down to the bottom of the separator and can be discharged. This removal is effective for aerosols in the size of 10-100 µm, if the cyclone is properly designed.

Secondary separation:

This form of separation is down by gravity settling. Therefore straightening vanes are used to reduce the velocity of the gas and bring it down to laminar flow. Due to this decrease the free fluid starts to accumulate on the plates and drops down to the liquid outlet.

This form of separation is only possible for big enough droplets. For smaller sizes the gravity force becomes negligible and the aerosols don’t accumulate. To get rid of these particles it is necessary that they agglomerate, before they can be separated.

Mist extraction (demister):

This part of the separator consists of a wire mesh package with small porosity. The gas flows through this mesh and the liquid droplets coalesce on the wires. When they are big enough, the droplets start to fall down and are then discharged at the bottom. The maximum thickness of these packages is normally 150 mm, because beyond this the total separation rate can’t be increased sophisticatedly. A problem for this part of the separator can be, if the liquid amount is larger than calculated, because then it gets flooded and parts of the fluid enter again the gas stream. This form of a separator can segregate droplets of a size from 5-10 µm, but the extraction rate is not 100 %. The only possibility to separate also smaller particles is a filter separator.

The other possibility to reduce mist is a plate fin. This uses the effect of impaction, because the gas stream must flow between such plates, while the droplets can’t follow fast enough and collide with the fins. Due to the velocity change the drops start to accumulate on these plates.

When gas is only dried with usual separators, then some liquid is normally left in the gas stream. The size of these particles is according to the scientific report of Pall corp. the following, showed in fig. 13:

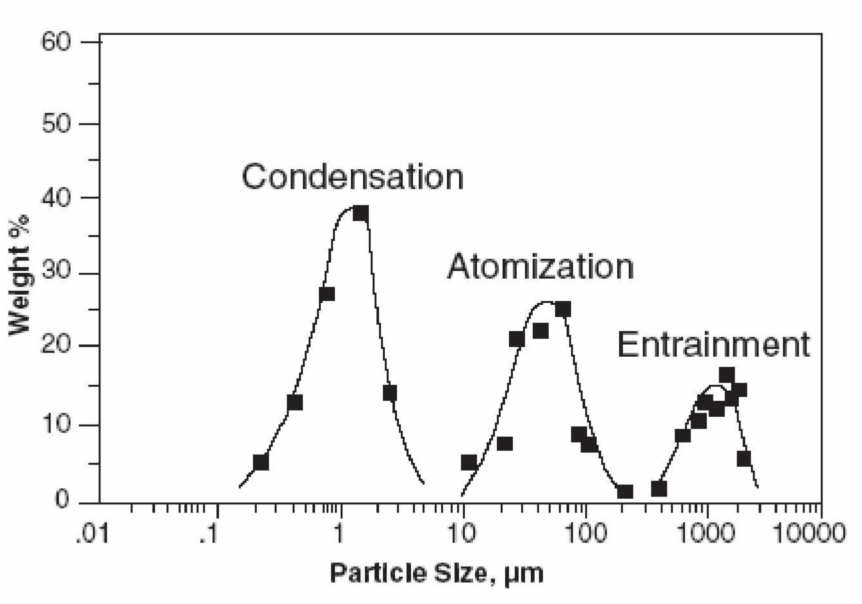

Figure 13: Aerosol size distribution after normal separation

Due to the fact that the gas flows always over some separation units, we can say that this must be the size distribution of the aerosols in the gas. Naturally there are some changes during the following flow period because of some condensation of liquids and the coagulation of particles. But if a filter separator is built directly after a normal separation unit, then this should be the aerosol distribution, which it should be able to extract.

Filter separation:

This type of separation is used for very fine solids and aerosol extraction. Aerosols in gas streams can be produced by condensation or by fluid entrainment in the gas stream. The particles, which are built through condensation, are normally smaller than 3 µm, while the second ones are larger. The measurement of aerosol size distribution can be done with a cascade impactor, but it is rarely made because of the too small utility in comparison to the price.

The particles, which such a separator can remove, are in the range of 0.1 µm and therefore in the smallest class of aerosols, which occur in natural gas streams. In the air also smaller aerosols are possible as it can be seen in the fig. 14.

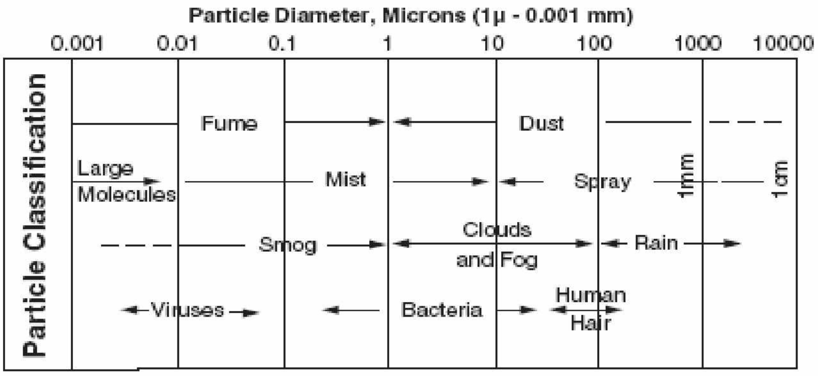

Figure 14: Aerosol size distribution

2.6.2. Methods for limitation of the liquids in natural gas

The most common way to minimize the amount of liquid in the gas stream is to write a paragraph about the gas quality in the contract. Often this is done with a sentence, which was constructed at the AGA Gas Measurement Committee Report 4a in 1971: “The gas shall be commercially free from dust, gum, gum forming constituents and liquids at pressure and temperature at which the gas is delivered.” The problem in this formulation is that with reduction of pressure and temperature liquid can drop out after the delivery. Then the contractor is not reasonable for the liquid, but it is present in the gas. Therefore also other regulations are used to get liquid problems under control.

Some corporations use the determination of a maximum heating value to regulate the liquid drop outs. However, the heating value of a gas is not necessarily high, when the C6+ value is high and also the other way round. For example when a gas contains much ethane and no C6+ fraction the heating value is high, but the hydrocarbon dewpoint would be low.

Another tool sometimes used is the control of the percentage of C_{5+} or C_{6+} in the gas stream. This specification can also not provide that liquid will drop out, because not only the amount of C_{6+} but the composition is reasonable for the hydrocarbon dewpoint. This composition is changing over the length of a pipeline and thus at some points in the pipes liquid can condense.

Hence the most reliable possibility to prevent fluid drop out is to limit the hydrocarbon and water dewpoints themselves. The problems related to this are the inexact measurement and that always only one dewpoint for a specified pressure can be measured. Therefore it is possible that liquid is built due to retrograde condensation or because of a composition change downstream the measured point.

Another way to solve this problem is the reduction of heavy hydrocarbons with low temperature gas drying units. These facilities cool down the gas stream below the dewpoint, then the fluids condense and at least they are mechanical removed.

Several kinds of these constructions are known. Generally they can be divided into low temperature installation with gas expansion, such with a refrigeration unit and units with expanders.

A method to limit the glycol amount in the gas is to change the dehydration equipment to adsorption units. There the gas flows through a drying bed, where the water is removed. These beds must be regenerated, when they are loaded, then they can be used again. It is possible to remove also heavy hydrocarbons (C_{6+}) with these installations, but for this kind of cleaning the regeneration cycles must be shorten drastically from several hours to around 20 minutes.

2.7. Case study: East Javagas Pipeline

The East Javagas pipeline, shown in figure 15, connects the isle Pagerungan with Java Island. It is around 400 kilometres long and transports dry sales gas. The maximum capacity is at 600 MMSFD with an inlet pressure of 1800 psi. Actually it transports at a pressure of 1200 psi half of the designed volume.

During the operations in the Pagerungan plant a failure occurred and the dry gas composition changed to wet gas. This means that the fraction of the heavy hydrocarbons increased. Due to this problem liquid condensed in the pipeline. More than 430 barrels were caught in liquid slug catchers. The question, which came up afterwards, was whether some fluids were left in the system or not.

The problem was simulated with the computer program OLGA. Therefore the necessary data was collected and then six different cases were simulated. The conclusion how the liquid behaved in the pipeline were the following: The fluid, which condensed in the pipe, started to accumulate 20 hours after their building at the low points of the pipeline. An additional factor for the accumulation was the slope after a low point. The higher it was the larger was the liquid accumulation. An experiment was done with water to get more details about the behaviour of the fluid in the pipe. This water also accumulated at the bottom points and when no more liquid came from the upstream part of the pipe, the liquid slug got removed due to the high velocity of the gas. After seven days the first liquid flowed out of the pipe and after ten days the whole system was dry again. This experiment showed that in a pipe were permanent gas flows no accumulations can exist over long periods, when the gas velocity is high enough.

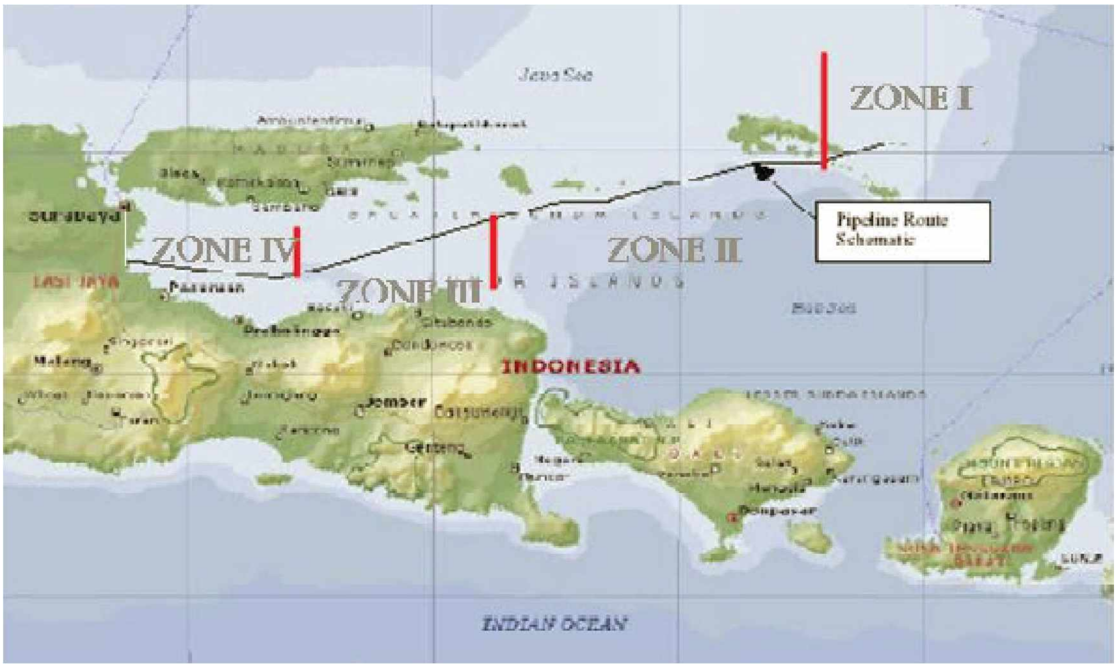

Figure 15: East Javagas pipeline [13]

3. Practical Application

3.1. Problem description

In the year 2004 the GasNetz Steiermark determined liquids in the pressure reduction station Bauernfeind in Rothleiten and at their customer Mayr Melnhof in Frohnleiten. For this reason the high pressure pipeline system, which lies before these points, was checked and fluids could be determined at the stations G4 and G5. These liquids were analysed and the results have been that they were a product of machine oil of HD 32 from OMV and unidentified machine oil, which possibly comes from other compressor stations not controlled by OMV. The rest of the fluid was a mixture of aqueous triethylene and diethylene glycol.

No significant amount of these liquids was separated in the upstream high pressure pipelines of OMV, although filter separators are installed and checked continuously.

These fluids can be found in the downstream region, despite this fact that before every compressor station and also at the off take points the gas was filtered. The question is whether the particles are too small to be filtered or are they generated at a point after the filters.

3.2. Description of the TAG pipeline system

3.2.1. Transition gas in Austria

Today Austria has a key position for the transport of Russian gas to Europe. This is a consequence of a long tradition, which started already in the 1950`s, when people thought about the necessity of the gas import for Austria. This leaded to the building of the PVS, the “Primärverteilungssystem”. It started to work in 1968 and had a length of 351.9 km. However since the 1970`s the first real transition pipeline was operated, the TAG 1. The first gas flowed through it in 1974. This was the time when Austria as the first country made a contract with the UDSSR. The pipeline system was enlarged in the next years to bring the gas not only to Italy, but also to Slovenia and Hungary. The increase of the system, made it necessary to build additional compressor stations along the lines. Today along the TAG three compressor stations exist. The largest is located in Baumgarten, Niederösterreich, where now the seventh compressor starts its work. The others are in Grafendorf, Steiermark and in Ruden, Kärnten. The gas that flows nowadays through the TAG flows on the one hand from Russia and on the other hand from the Slovakian gas storage in Lab. It is separated, filtered and measured in Baumgarten, when it enters the station. There also the quality of the gas is controlled continuously by a gas chromatograph. Three times a week the hydrocarbon dewpoint is measured and the water dew point is constantly controlled. If it comes above minus six degree Celsius, the gas is directed over the glycol dehydrating units. It is possible that this is not the case during a year, but in 2007 the glycol units worked already for 2 weeks, one in August and the other in October. During every start up phase some glycol is lost into the system. The amount of glycol that is lost in this phase can be several hundred litres of glycol. Afterwards during normal operation the losses are very low and can be nearly neglected.

The amount of gas that flows through the TAG system in one year exceeds 41.5 billion cubic meter of gas and is still increasing. To provide corrosion and failures at the compressor stations the gas is filtered when it enters a station. However the gas is already dried and only small amounts of liquid accumulates there. These filters are designed for one micron diameter particles, so that only very small particles could migrate through the system and this would normally not harm the compressors. These compressors are driven by powerful gas turbines with up to 22 MW power. The entrance pressure of the compressors is at 45 bar and the output pressure reaches 70 bar. All parts of the TAG pipeline system are piggable and every 5 years intelligent pigs are driven through the pipes. This provides that no corrosion failures can happen and that no liquid accumulates in the system.

3.2.2. Topography of the TAG

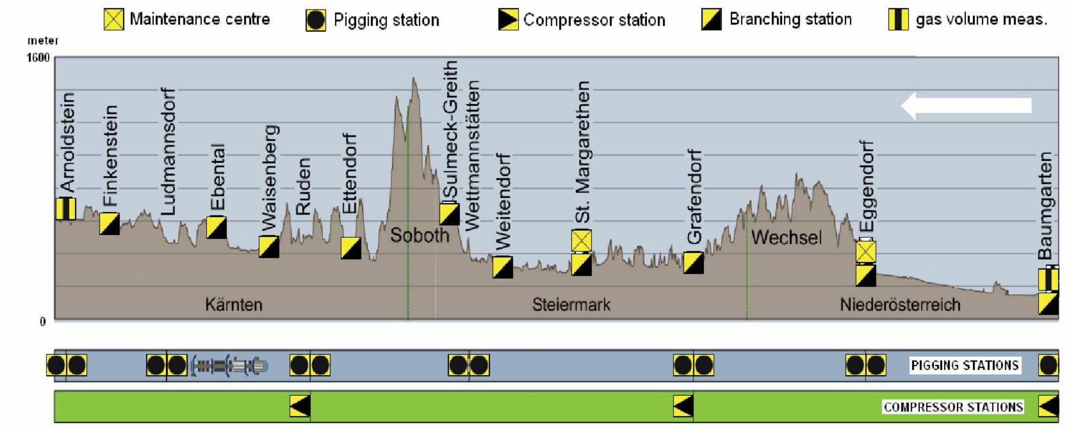

Figure 16: TAG pigging and compressor stations from Baumgarten to Arnoldstein

The TAG pipeline, displayed in fig. 16, starts at the Slovakian border and ends in Arnoldstein at the Italian border. In between are three intake points at Baumgarten, where also the first compressor station is located. The other nine offtake points are marked at the map above. They supply the Austrian gas distribution system and at Weitendorf the SOL pipeline system starts to Slovenia. To achieve the necessary pressure in the pipes three compressor stations are located along the line. The first is in Baumgarten. There are four GE Frame 3 gas turbines with 11 MW and three PGT 25 DLE with 22 MW ISO power, which are compressing the gas up to 70 bar. At this station the gas gets also dehydrated via five glycol drying units and it is filtered to get rid of the solid particles which could move with the gas. Moreover the first fiscal metering station is installed at Baumgarten. The others are at Arnoldstein and the other offtake points along the pipeline.

The second compressor station is in Grafendorf approximately 135 kilometres behind Baumgarten and the last is in Ruden 150 kilometres behind Grafendorf.

Another installation in the pipeline are the safety valves every 20 kilometres, which can isolate the sections of the TAG for maintenance or when a problem with leakage occurs. These chokes can be operated by the OMV gas dispatching centre in Vienna or from the local compressor stations. The total amount of valves is 36 distributed over all three lines.

The topography of the TAG shows an undulating hilly terrain as it can be seen in fig. 17, where the changes between minimum and maximum sea level are very large. The top point of the pipelines TAG 2 and TAG Loop lies above 1200 meters, while the lowest point is less than 200 meters, which means a height difference of more than 1000 meters. The TAG 1 doesn't make these big jumps and has as maximum diversity around 400 meters difference between top and bottom.

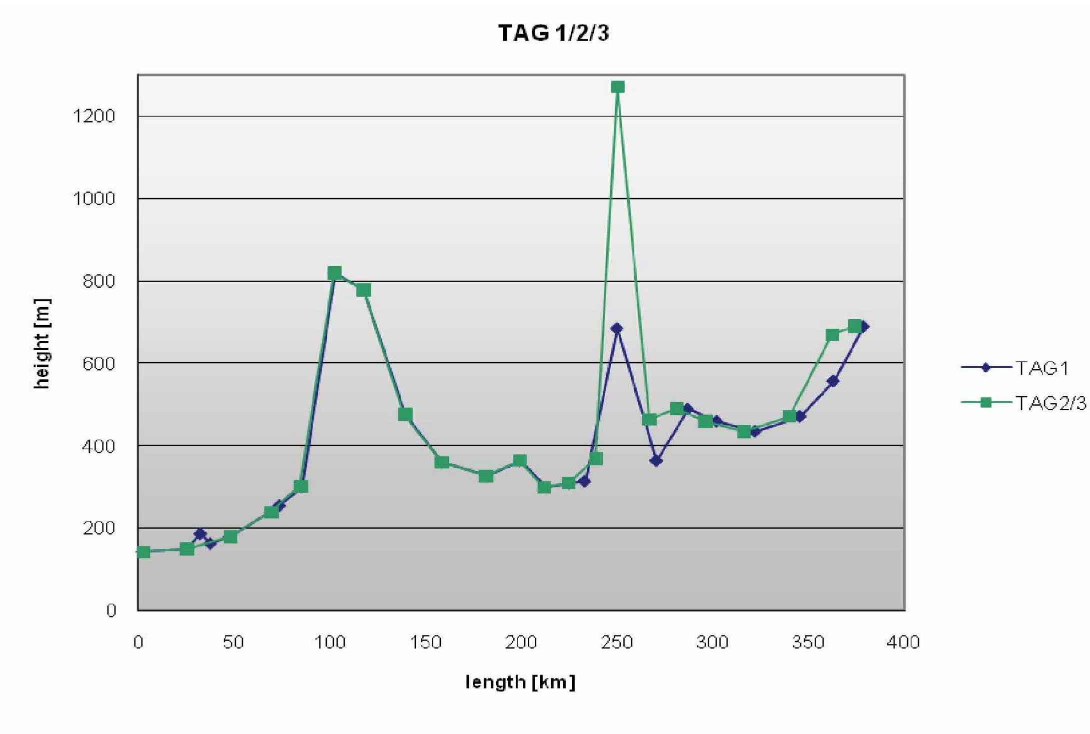

Figure 17: TAG topography from Baumgarten to Arnoldstein

3.2.3. System equipment description

Filtration technology :

The separation in the TAG is done at every compressor station and also at the branching stations. For that normal separators based on segregation forces and also some filter coalescers are used. A new coalescer from "Filtan" was installed in Weitendorf last year for special protection of the "Gasnetz Steiermark". This separator has the following design parameters:

max. gas amount	250 000	Nm^3/h
min. working temp.	-10	°C
max. working temp.	+50	°C
min. working press.	50	bar
max. working press.	70	bar
coalescing area	16	m^2
separation rate	**>1 µm**	**99.90 %**
	>3 µm	**99.99 %**
pressure drop	~100	mbar

Table 2: Filter design

These parameters should be sufficient to filter 80 to 90 percent of all aerosols in the gas stream, because the aerosol distribution after normal separators is mostly above 1 µm. The amount of fluid in the separator, which was found since the filter was installed, was in the range of 15 litres. This means that in one year since the installation a fluid amount of about 1.5 to 3.75 litres flew through the separator into the pipeline net of the GNS. The average gas amount per hour is 74 073.31 m^3. When this value is summed up for one year leads this to an amount of 648 882 195.6 m^3/a. The mass of 3.75 l in the gas is equivalent to a percentage of 5.8*10^{-10} %.

Gas turbines and compressors:

During the flow of gas from the wellhead to the customer it has to be compressed several times due to pressure losses. Also when it should be stored in an underground gas storage and the most important compression is for the international gas transmission lines. These pipes are usually made for operating pressures between 50 and 70 bar.

In general there exist two different types of compressors for natural gas compressing. The reciprocating compressor, which is built for low flow and high pressure ratios and the dynamic compressor, which is made for intermediate to high flow and lower ratios. It is subdivided into radial and axial compressors, which are only different in the compressing process and size. A radial one can be seen in fig. 18.

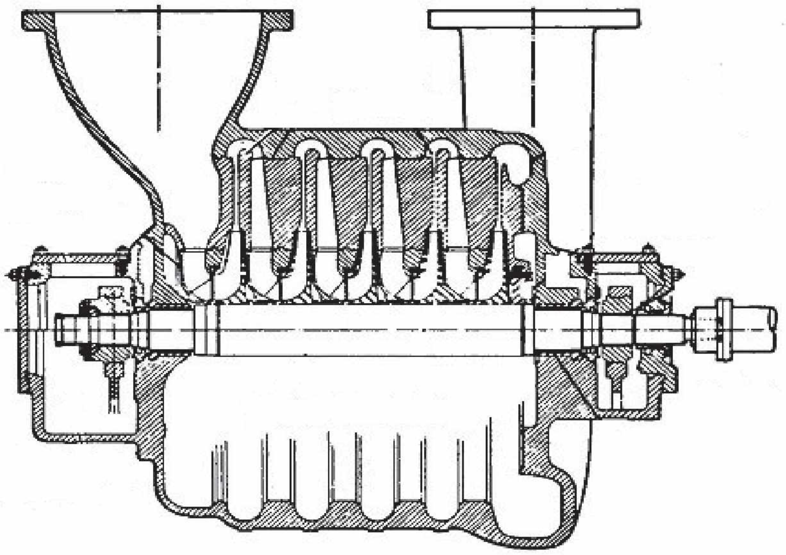

Figure 18: Radial compressor

According to the Standard handbook of petroleum and natural gas engineering the advantages and disadvantages can be summed up to the following:

Advantages of the dynamic compressor:

- low installation costs
- low maintenance costs
- high equipment dependability
- few service
- big volume capacity

Advantages of the reciprocating compressor:

- flexibility
- high efficiency and few energy supply costs
- high pressure ratios
- small sensitiveness to composition and density changes

A problem, which can occur with the dynamic compressors, is the surge. This means that the compressor cannot add enough energy to the fluid stream that it can overcome the internal system resistance. So at a given pressure the volume of gas goes below a certain limit and the stream breaks down. This leads to an inversion of the flow. If this is repeated several times, the compressor can be completely destroyed. Thus normally suction valves are installed behind a compressor. Another problem can be liquid at the compressor. Already small amounts are sufficient to generate fatal errors. For this reason drying units are installed at the entrance of a compressor station.

There are several possibilities to drive a compressor. One is a gas turbine. The functionality of a gas turbine is based on circle process called the Joule process. There air is compressed over several steps and the swept into a combustion chamber, where it is mixed with gas, ignited and then burnt. This generates hot gas which drives the motor itself and the following compressor. The turbines can be constructed with one shaft. For these types the motor and the compressor can be only driven at the same engine speed. The type with two shafts can be divided into a gas generator and a power turbine part. The gas generator unit has some turbine parts on it, which drive the compressor, while the power turbine is on the second shaft mounted with the motor. These units drive then normally a separate compressor unit, which is used to compress the transition gas.

Other possibilities to drive a compressor unit would be a gas motor, an electric motor, an otto motor or a diesel engine. The choice of the driving unit depends on the availability and the operation field of the compressor.

The compressor system itself consists of impellers and stators, which firstly accelerate the sucked gas and therefore the kinetic energy rises. Then the gas hits the stator, where this energy is changed into higher pressure and afterwards the next impeller follows. This compression of the gas leads to high temperatures, therefore the gas and the compressor needs cooling installations.

A totally other concept of compression has the reciprocating processor. It changes the circulating movement of the driving unit in an oscillating movement and then via a piston in compression of the gas. It is possible to build several types of these machines. They can be adapted as single acting or double acting. Another difference is if they are dry or lubricated. The first is very expensive, because everything must be constructed very smooth for this type of compressor, otherwise the wear would be extremely high. The problem with the second type of compressor is that it pollutes the compressed gas with oil. This oil can partly go into the gas phase and changes therefore the overall composition of the gas. Although reciprocating compressors are not used for the international gas transmission, the gas can come in contact with the oil at its way from the well head to the transmission line.

In Baumgarten GE NP PGT 25 DLE gas turbines and GE NP 41S3002 RC (Frame 3) are installed.

Figure 19: Compressor station in Baumgarten

PGT 25 aero derivative Gas Turbine:

The PGT 25 is a two shafted aero derivative gas turbine, which consists of a gas generator and a power turbine. The gas generator is a LM 2500, which is also used in aircrafts. It is built up of a 16 stage axial flow compressor, which can achieve a maximum pressure compression ratio of 18:1. There are inlet guide vanes and adjustable stator vanes, which are supporting the operating features at the compressor.

The power engine itself is the PGT 25 with 6500 RPM design speed with two expansion stages. The blade rows are at nozzles designed on cobalt, while the blades of the rotor itself are made on nickel base. The gas temperature on the inlet to the power turbine is quite moderate to enlarge the fatigue failure safety.

After the turbine a compressor type PCL- pipeline centrifugal compressor- is installed. A typical PGT 25 can be seen in fig. 20.

Figure 20: Nuovo Pignone PCL 603

Dehydration technology :

To reduce the water content of natural gas, which is normally carried out of the reservoir, several dehydration units have been developed. They can be divided into drying units with liquid absorption substances and with solid adsorption units. In Austria normally triethylene glycol is used. In earlier days also diethylene glycol and monoethylene glycol were often taken. Due to better absorption character of TEG, the use of other glycols was minimized.

The chemical composition of TEG is $C_6H_{14}O_4$:

It is built of ethanol and additional OH groups, which increase the ability of alcohol to take humidity of a gas and hold it. Therefore it is used to reduce the water dew point of gas in the range of 25 to 35 degree Celsius. The normal use for dehydration is downstream of a separator, which sweeps out the larger droplets of water. The gas comes into contact with the glycol in a contact tower with at least four bubble trays. The lean glycol becomes dispersed with the gas and absorbs the water. Then the dry gas runs through a demister where the glycol droplets should be held back and accumulate. However there exists a consumption of glycol during this process, which comes on the one hand from the distillation process for the regeneration of the rich glycol, but on the other hand it is caused by the carry over of some glycol to the pipelines with the dry gas. Normal consumption rates are between 5 and 16 litres per million cubic meters of gas.

Problems with TEG might be foam generation, which can occur when condensates are not totally swept out of the gas at the previous separator. This generation leads to insufficient rich glycol discharge at the bottom of the tower. For this reason the level of glycol rises and reaches at a sudden point the gas inlet and is then taken into the transporting line. To avoid this problem, scrubbers should be installed in the separator or defoaming agents should be mixed into the TEG. A typical installation can be seen in fig. 21.

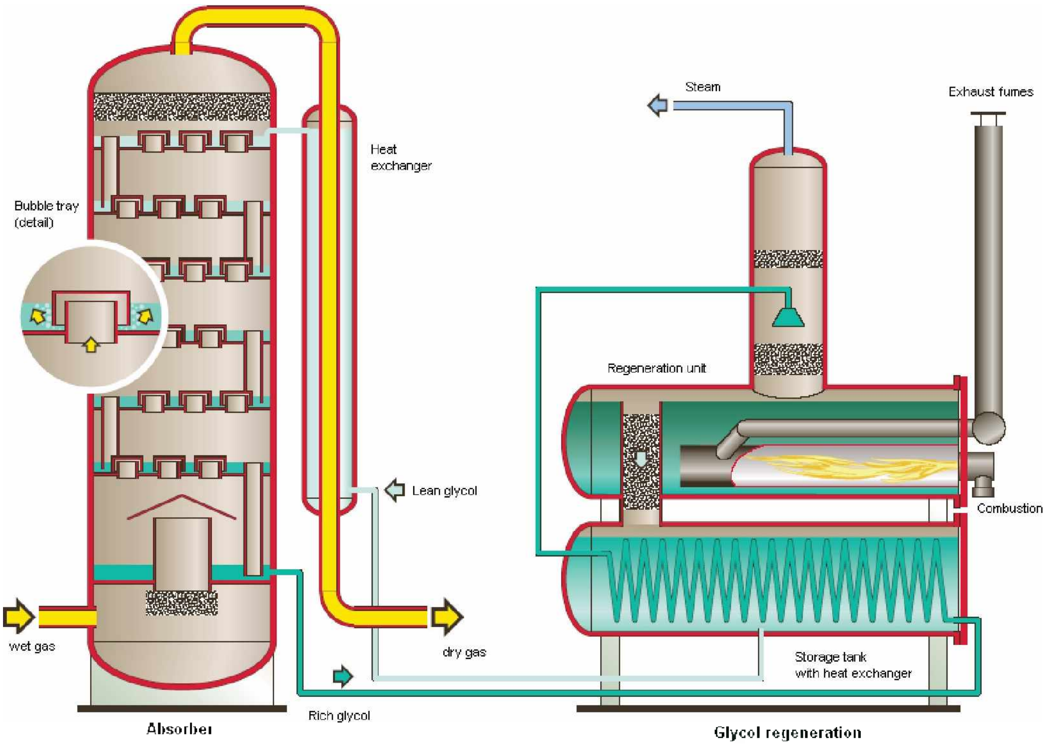

Figure 21: Glycol regeneration unit

<u>Dehydration process:</u>

The normal process is the following for dehydrating the glycol:

The gas comes from the well to the station and enters a first separator to sweep out the free liquid droplets. Then it enters the contact tower at the lower end, where a scrubber separates the condensates and water, which are generated during the upstream movement of the gas, and it is preheated before contacting with the glycol. The wet gas is moving upwards and comes into contact with the lean glycol, which is moving down. At the upper end the dry gas is leaving the tower and in a heat exchanger the temperature of the lean glycol is equalized to the temperature of the gas. The glycol itself is pumped in a closed cycle. After leaving the absorber at the lower end as rich glycol, it comes into a heat exchanger, where the glycol is preheated. The next step is that it enters the distillation column, where the glycol is dried via fractional distillation. The reboiler below is normally directly fired by a burner, and heats up the glycol. Therefore the water is evaporating out of it and moves up through the column directly to the atmosphere. If a part of the glycol is taken with the water vapour, then it condenses again at some cooling features at the upper part of the column and drops back. This don't have an efficiency of hundred percent, because as mentioned above between 5 and 16 litres per million cubic meter dried gas is lost. The now again made lean glycol can be concentrated up to 99 percent. The hot glycol has to be cooled down, because the absorption process is very sensitive to contact temperature changes. Thus the hot glycol is used to preheat the rich glycol and then comes into a second heat exchanger where gas and glycol temperature are equalized.

Dependent on the concentration of the glycol the circulation amount, which is necessary to dry the gas, is increasing. Normally a rate between 25 and 60 kg TEG per litre water vapour is chosen. For the reconditioning of the TEG the fractional distilled. This generally is sufficient since the boiling of water is at 100°C whereas the boiling point of TEG is at 285.5°C. Hence the reboiler temperature is not above 204°C, because it is sufficient for the reconcentration and TEG starts to decompose thermally at this temperature, when it is heated further. The thermal cracking from TEG to DEG can partially happen below this temperature and may be the reason for finding DEG in the liquid samples. Another possibility to increase the glycol concentration would be vacuum distillation or the use of stripper gas, which lowers the partial pressure of water.

Corrosion problems with TEG:

The TEG, which is carried out from the dehydration units to the pipeline system, can lead to the corrosion of the line. The pH value of the TEG is normally decreased because of thermic processes. This TEG in the system has longer contact with the gas as usual. Therefore it enriches with water and accumulates at the deepest points of the line. Then it acts like an acid and starts destroying the pipe.

To reach very deep dewpoints or if the gas temperature is high glycol is not the optimal choice. For these cases packed bed with adsorption processes should be taken.

Under the conditions usually found in transport pipelines, glycols exist in liquid phase.

The melting point of diethylene glycol is at -7.8 °C and for triethylene glycol at -4.3 °C at one bar, while the bubble points are at 245.5 and 288.0 °C. Due the reason that the operating pressure is much higher and the operating temperature is below the boiling point, it is not expectable that the glycol will change its phase.

3.2.4. Pipeline design TAG

The TAG pipeline system consists of the TAG 1, which was installed in 1974. It has a pipe diameter of 38” and 36”. It has a length of 382 km and is constructed of carbon steel X-60. The next pipeline, which was installed, was the TAG 2 in 1988 with a length of 377 km, the material of X-70 and a diameter of 42”. The last expansion was made with the TAG Loop 2, which was made in several stages. The last one was finished in 2006. It has a length of 376 km, a material of L 485 MB and a diameter of 40”.

All three lines are laid in a minimum depth of 1.5 meters except for river crossings. There exist only underwater solutions and no crossing via bridges or elevators. The most important rivers are the Danube, where the pipes have to cross a length of 970 meters and the Drau with 468 meters.

The whole system is only constructed for the transport of sweet gas, so the acid components as CO_2 and H_2S must not exceed very small limitations. Further construction boundaries are the operating pressure of 70 bar and the temperature of 50 °C. All pipes are at some point interconnected and share the same pressure level.

The inspection and pigging stations are located at a maximum distance along the pipe line of 70 kilometres. At these points the pigs for dewatering and inspections can be put into the line or taken out. Every six years in the TAG 1 and every eight years in TAG 2 and TAG Loop 2 intelligent pigs are used to control wall thickness and areas of corrosion problems and cracks.

The first branching station is located in Eggendorf and supports the distributing system of EVN. It is connected with the node Wiener Neustadt and the EVN pipe line South West 2. The used pipe for the supply is a 16" one, which is branching here from the main TAG stream with 38" at this point. The next branch is Grafendorf with 8 inch, where the customers are BEGAS and STGW. One of the liquid samples was delivered by BEGAS. At St. Margarethen a side arm with 6 inch diameter is installed for the STGW. The following branch is located in Weitendorf and has a 16 inch pipe connection. The customer here is the STGW, which reported problems for this line with liquids. The other arm in Weitendorf is a 20 inch connection with the SOL, where also some liquid problems were recognized at the Murfeld. The next junction is placed in Sulmeck-Greith, which is feed via an 8 inch pipeline. The recipient is again STGW, for the branches afterwards is the customer always KELAG. Ettendorf is the following branch off station, which has an 8 inch supply line. After this is a compressor station in Ruden located. The next arms are Waisenberg (6 inch), Ebenthal (8 inch) and Finkenstein (8 inch). At the end of the TAG at the Italian border lays Arnoldstein, where the last metering station is located. All stations are equipped with filter separators, which shall remove any liquid in the TAG.

3.2.5. Regulation of gas composition by the ÖVGW G31

Due to the fact that the gas in the TAG comes not only from the intake point at Baumgarten from the SPP, the gas composition changes from the intake point to the offtake point at Arnoldstein. The other intake points are the connection with the OMV Gas GmbH at Baumgarten, where the gas, which is produced in Austria, is introduced into TAG system and the intake point from the WAG, which is also in Baumgarten. Nevertheless the composition must stay into the range of the ÖVGW G31, which can be seen in tab. 3.

Quality criteria of the ÖVGW G 31 [ÖVGW 2001]		
1.	Wobbe-Index	13.3 – 15.7 kWh/m³
2.	Upper heating value	10.7 – 12.8 kWh/m³
3.	Relative density	0.55 – 0.65
4.	HC dewpoint	max. 0°C at oper. press.
5.	water dewpoint	max. -8°C at 40 bar
6.	O_2	< 0.5 Vol. %
8.	CO_2	< 2 Vol. %
9.	N_2	< 5 Vol. %
10.	H_2	< 4 Vol. %
11.	Total sulphur	10 mg S/m³ (cont. basis)
30 mg S/m³ (average)		
12.	Mercaptan sulphur	< 6 mg S/m³
13.	H_2S	< 5 mg/m³
14.	COS	< 5 mg/m³
15.	Halogen compounds	0 mg/m³
16.	NH_3	technical clean
17.	solid and liquid particles	technical clean
Other substances, which endanger the operating safety, must be avoided.		

Table 3: Gas composition due to ÖVGW G31

The natural gas shall be practically free of solids, dust, iron oxide, mud, liquid hydrocarbons, resins, resin forming constituents and shall not be odorised. This specification has quite high maxima for the single components, because according to the EASEE guidelines, which is the European association for the streamlining of energy exchange, where the AGGM (Austrian gas grid management AG), the control area manager for the Eastern control area, is a member, the parameter settings should be stricter.

3.2.6. Composition of the sales gas in the TAG system

The composition of the gas is normally measured via gas chromatography in front of the compressor stations. There the normal range that is measured goes up to only C_{6+}. For the determination of the phase diagram is this measurement not precise enough. It leads to an under-prediction of the hydrocarbon dew points, which are measured in the TAG three times a week.

Therefore the below seen values are only taken for the evaluation of average values of the composition till C6. The rest has to be combined out of the condensate and the HTU-AS 32 analysis.

In the year 2007 the overall gas composition starts changing and shows the trend that the heavier hydrocarbon content increases. The increase of liquid in the last year could be a consequence of the completion of TAG loop 2, which made it necessary to connect some dead ends with the rest of the pipeline system. In these ends additional fluid was found.

The maximum amounts of heavier hydrocarbons were measured in the months October, November and December, which concluded into the following data:

C_2	1.35%
C_3	0.44%
C_4	0.11%
C_5	0.03
C_{6+}	0.015

Table 4:Sales gas composition

3.3. Analyses of liquid probes

The gas composition was analyzed to determine the possible condensate amount and the influence of lubricating oils. Furthermore the liquefiable amount of glycol in the gas stream was determined and added to the total portion of fluid.

After subdividing the possible fluid amounts in three scenarios, the minimum, maximum and most likely case, the resulting transportation modes can be modelled. This should give the hint, how the fluid can enter the downstream section through filters and separators.

The starting point of my search was the liquid analyses, which were taken in the past. I found out that in the last two years eleven liquid samples from the TAG pipeline system and corresponding distribution systems, where analysed by gas chromatography. Although this can be only a small part of the total amount of liquid, which is found in the bottom points of the pipeline, the samples are certainly representative for the liquid transported in the system. The total amount in the last three years was:

2005	930 litres
2006	980 litres
2007	1800+ litres

The analyses made it possible to divide the fluids in two groups, shown in fig. 22. The liquid consisted in one case of two phases and in the other only of one. The first phase was built up by an aqueous solution, which contained TEG and DEG, and the second phase had a composition of condensates. As it can be seen in the gas chromatogram below this phase was made up of two parts; the first, which consists only of condensate. For this kind of fluid a deeper analysis of the exact composition was necessary, because they could have only developed by retrograde gas condensation.

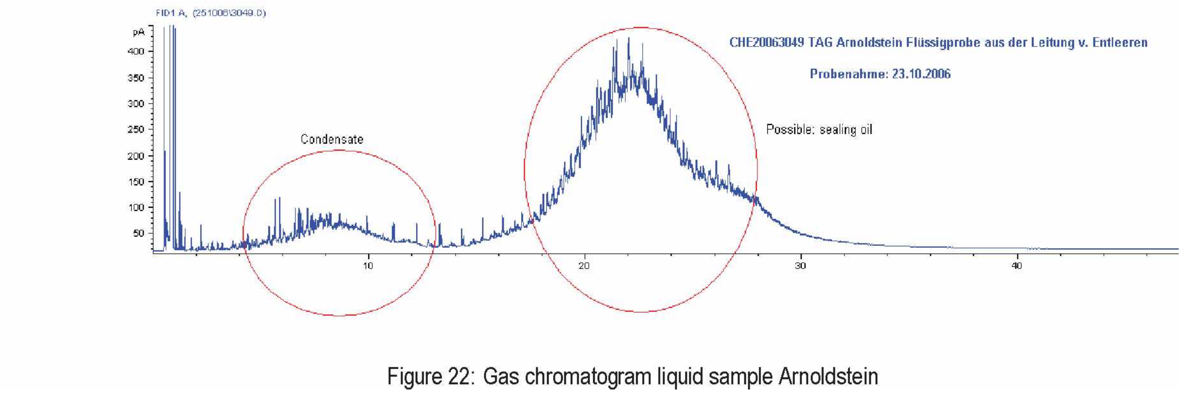

Figure 22: Gas chromatogram liquid sample Arnoldstein

Here we can see at the left side a high peak of light condensates around C_6, which comes either from unclean sample taken or from gas, which was solved into the condensate. The second hump is composed of the mentioned condensates and the last hill consists probably of turbine sealing oil. The next figure shows a comparison of the normally taken sealing oil HTU-A8-32 with the second peak in the samples. It can be seen in fig. 23 that the composition shows a high similarity, which leads to the conclusion that the peak is generated by this oil.

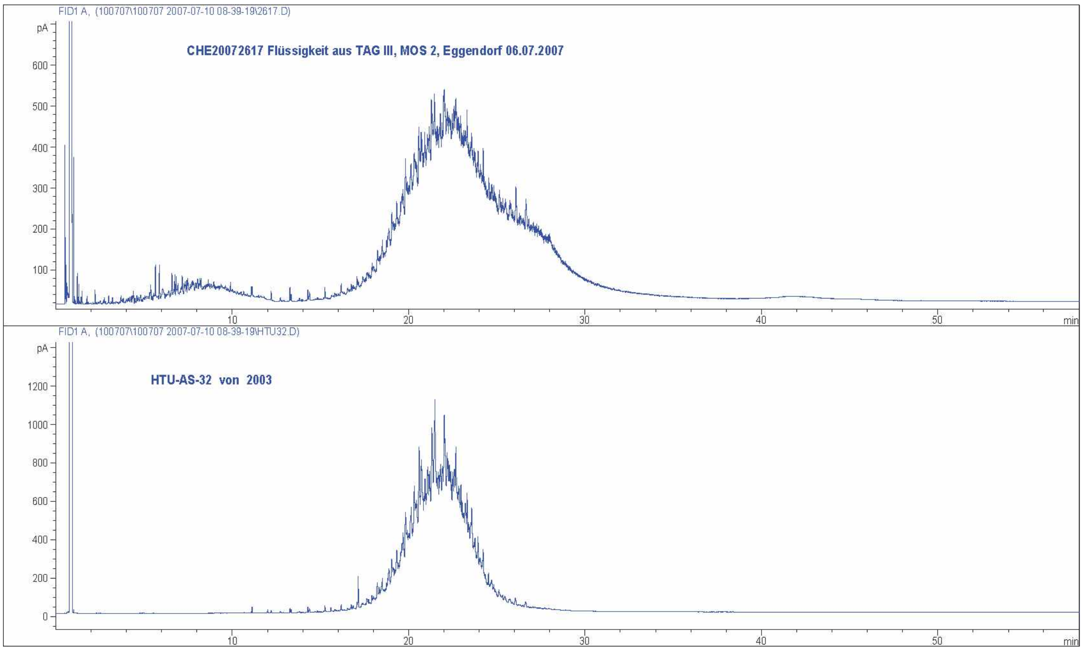

Figure 23: Gas chromatogram liquid sample Arnoldstein and comparison of HTU-AS 32

In several samples also some corrosion products were found, which consisted of iron oxide.

3.4. Measurement of HC dewpoint

3.4.1. Measurement of HC dewpoint in the TAG

The hydrocarbon dewpoint of the sales gas in the TAG pipeline system is only measured at the Baumgarten station. It is done three times a week before the compressors and once a month after the compressors. The value of the dewpoint lies during one year between -8 and -16 degree Celsius at a pressure of 50 bar. Behind the compressor the measured value is in the same range but for 70 bar. This means that the phase diagram has been shifted to the right side. In the last month till October the measured dewpoints have slightly increased, which is caused by the change of composition of the import gas.

The measurement is done by the chilled mirror method always by the analyser. The problem with this method is that the measured values are uncertain. This technique is based on the cooling of a small mirror with propane gas, while a probe head takes samples from the sales gas stream. These samples are flowing along the mirror and when the mirror reaches the dew point temperature then the first liquid droplets form. This temperature of the mirror is then read off via a thermometer. It is a quite common method, because it can be done very easily and is cheap.

3.4.2. Problems with the chilled mirror measurement

The chilled mirror measurement has some uncertainties, because the observation of the first liquid drop depends strongly on the person, who is doing the measurement. The result of the measurement can vary up to 15°C, if the mirror is cooled down too rapidly. Another possible source for a failure is the presence of glycol or water in the gas, which is the case in the TAG. It can drop out before the hydrocarbons start to condense and this can be read off as HC dewpoint. Normally it can be said that this method is under predicting the hydrocarbon dewpoint. As the chart in fig. 24 shows the liquid that drops out on the surface of the mirror, is not a linear function but has a sudden increase at which than often the condensate is firstly seen.

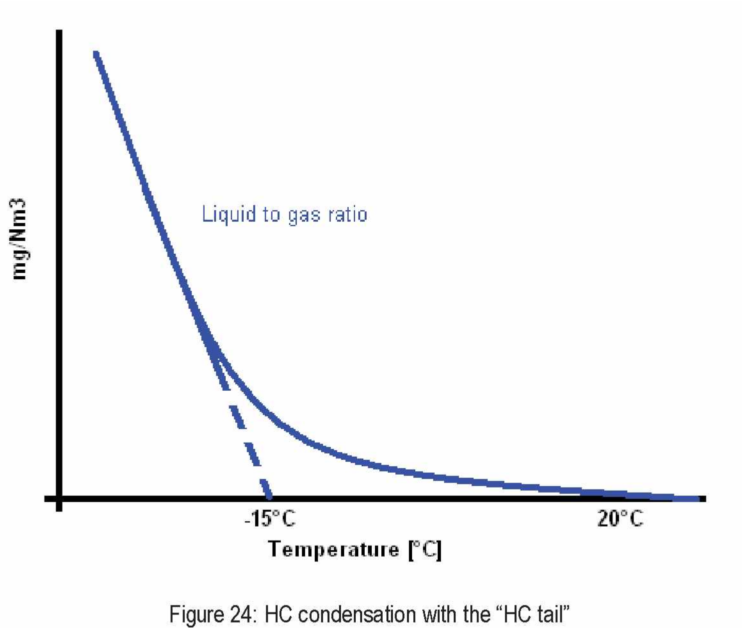

Figure 24: HC condensation with the "HC tail"

Dustman et al.(36) pointed out that an only experienced technician should make the chilled mirror analysis. Those people have standard deviations to other methods between 5 and 10 °C, while an unskilled technician can measure dewpoints, which differ more than 15°C from calculations.

3.4.3. Other methods for measuring the HC dewpoints

Another possibility for determining the dewpoint of the gas in the pipeline would be a gas chromatography, which can also detect the smallest amounts of heavy hydrocarbons and then calculates the dewpoint with and equation of state. The problem with this method is that also heavy alkanes, which exist only the ppb range, can influence the dewpoint significantly. A system that can measure this with a good significance would be very expensive and is probably not available for field conditions. Therefore this type of equipment is not recommendable for the TAG.

The third method, which can be used for dewpoint determination is the measurement of the potential hydrocarbon liquid content, which can be correlated to the real dew point. This method is also quite complicated and expensive for field installations.

Therefore some authors advise an improvement of the first method. This means that the subjective part of the measurement is substituted by an electro-optical measurement. There exist methods, which allow measuring the first condensate, when it is still in the ppm region and thus it is more precise than the normal optical method.

One very popular method is the dark spot technique. It uses a red light, which is reflected from a specially treated surface, thus it forms an annulus around a detector, which is in the dark spot, as it can be seen in fig. 25. This detector measures only the scattered light that intrudes in this spot. When liquid starts to drop out on this surface the amount of dispersed light on the detector reduces. When this happens the temperature of this surface is recognized and this is then the hydrocarbon dewpoint. This evaluation can be applied to a wide range of different ambient and HCDP temperatures.

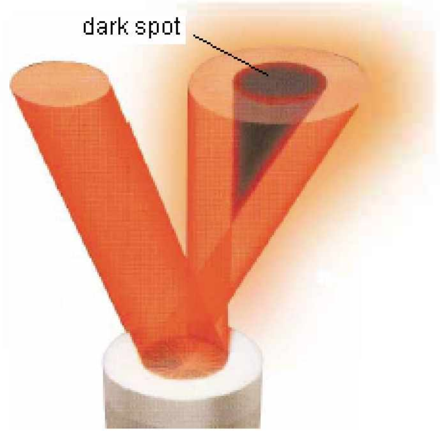

Figure 25: Dark spot principle

3.5. Phase diagrams of the gas

For identifying regions, which are endangered off building liquids, the correct phase diagram for the gas composition has to be found. This is a very complex problem, because of the changes of the components at compressor stations, accumulations of liquid during the transport that changes the overall composition and because of branches were also the mixture of the gas can be changed.

Therefore three cases were built. The first case includes only the average gas composition of the sales gas in the TAG and all components above C_6 were ignored. This would be the ideal case for the gas composition displayed in tab. 5 and fig. 26.

COMPONENT	%
CO_2	0.13
N_2	0.78
C_1	97.64
C_2	0.99
C_3	0.32
i-C_4	0.05
n-C_4	0.06
i-C_5	0.01
n-C_5	0.01
C_6	0.01

Table 5: Ideal gas composition 2

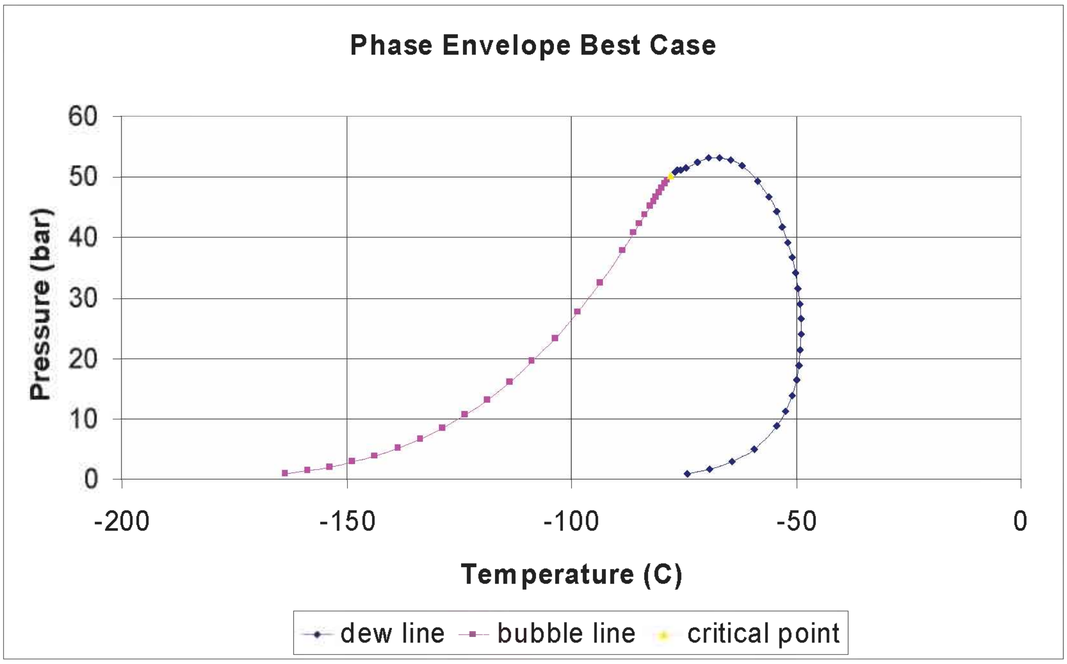

Figure 26: Phase diagram: ideal composition

It can be seen easily that out of such a gas liquid cannot drop out under normal operating conditions. Furthermore it is clear that this is not the normal composition, because out of hydrocarbon dewpoint measurements, which were in the range of -8°C and -16°C at a pressure of plus/minus 50 bar.

Out of the information about the HC dewpoints and the composition of the condensate found, the mixture of the most likely case was built.

3.5.1. K-factors and mole fractions correlation

This correlation was built on the fact that separation of the liquid and the gas has taken place, when condensate probes are taken to the laboratory and analysed. It is an unconventional method and should not be extrapolated as general solution.

The so called K-factors can be calculated by the following formula:

$$K_i = \frac{\exp\left(5.37 * (1+\omega_i) * (1-T_{Ri}^{-1})\right)}{p_{Ri}} \tag{24}$$

ω_i ...acentric factor

T_{Ri} ...reduced temperature

p_{Ri} ...reduced pressure

For this formula the reduced properties and the acentric factor factors are needed. For the calculation of the reduced properties the critical properties and standard temperature and pressure were taken.

The composition of the vapour phase was evaluated by the average of the sales gas composition till C6+. This was then calculated with the K-factors on the parts which had to be in the liquid part, but were evaporated due to the fact that the sample box for the fluids are not gas tight.

$$K_i = \frac{y_i}{x_i} \tag{25}$$

x_i… liquid mol fraction

y_i… vapour mol fraction

The analysis of the C7+ fraction was done with the evaluation of the condensate composition. Both pieces of information were combined and the values for the composition of the fluid could now be calculated back with the above mentioned formula to the gas composition.

The problem with this calculation is that the part of C_6 must be estimated, because neither in the gas composition nor in the condensate analysis the C_6 fraction is directly measured. The estimate was based on the standard correlation described below.

This analysis leaded to a phase diagram, which is better predicting the measured hydrocarbon values than that before. All phase diagrams were calculated with GAS

VLE on the basis of the Peng Robinson equation of state and the result is displayed in tab. 6 and fig. 27.

COMPONENT	%
CO_2	0.13
N_2	0.78
C_1	97.63
C_2	0.99
C_3	0.32
i-C_4	0.05
n-C_4	0.06
i-C_5	0.01
n-C_5	0.01
C6	0.01996
C7	1.198E-07
C8	1.2699E-06
C9	5.8702E-07
C10	1.1181E-06
C11	4.3288E-06
C12	7.4715E-06
C13	9.7437E-06
C14	8.4419E-06
C15	4.4725E-06
C16	2.38E-06

Table 6: Most likely gas composition

If now the normal operating conditions are introduced into this diagram, it can be seen that for this most likely case no condensation fluid can be formed. This is also the experience of the TAG that at most places and fluid is found only seldom.

However, some condensate is found over the whole length of the TAG. Thus there are only two possibilities how fluids can be formed. One is that the normal operating conditions are exceeded and the other can be the modification of the gas due to changes of the input gas composition or by the entrance of heavier hydrocarbons at the gas compressors.

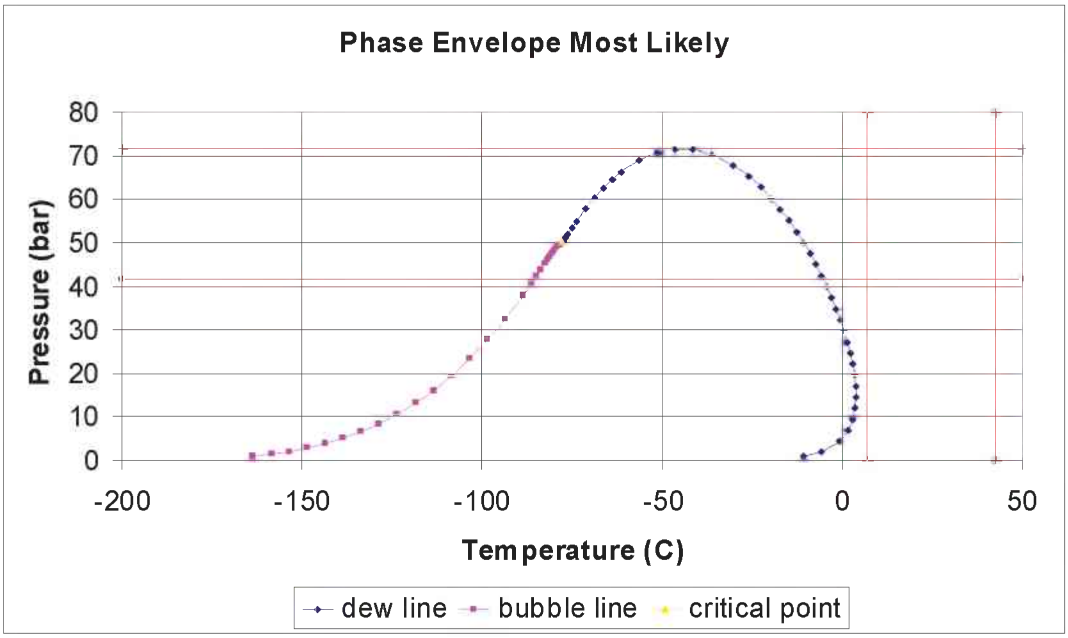

Figure 27: Phase diagram: most likely composition with operating conditions

This variation in the composition leads then to the worst case for the phase diagram. The oil, which is used at the compressor stations, was analysed and the exact composition was developed. For building the phase diagram the most likely composition was taken and the components of the sealing oil. These were evaluated via gas chromatography. The amount, how much oil must be taken into consideration, was dependent on the scenario for a single case. There the approach was that 55 litres of sealing oil is lost into 1.5 million cubic meter of gas. This happens not during normal working operations of the compressors, but it would be possible for malfunctions of the sealing unit of one gas compressor.

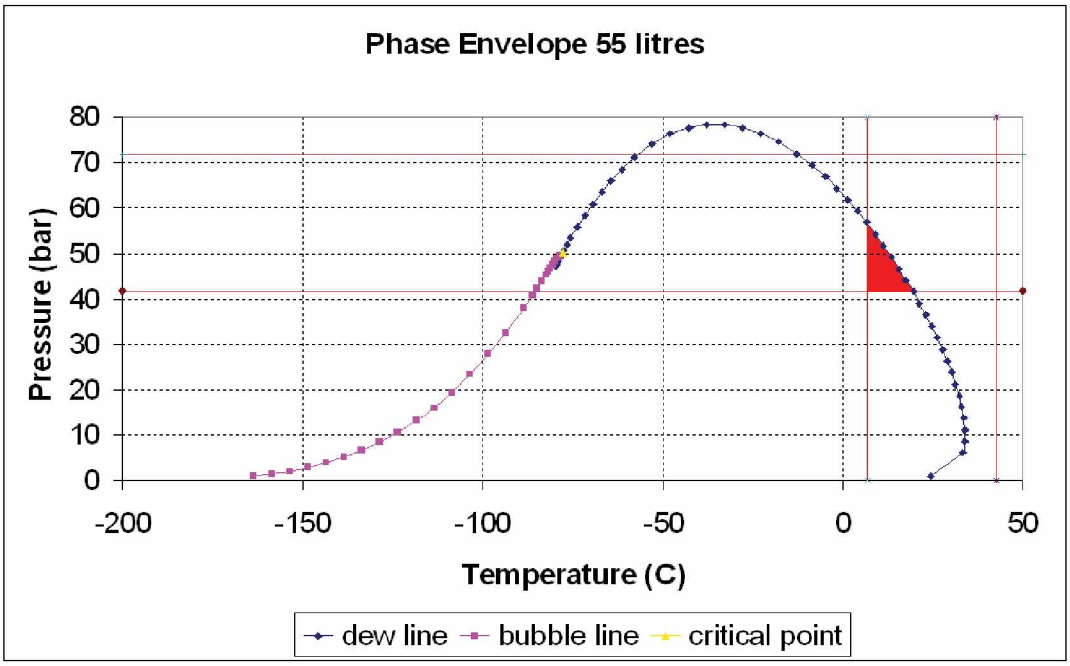

Figure 28: Phase diagram: worst case with operating conditions

The fig. 28 shows that the operating conditions come clearly in the two phase region and liquid will start to drop out of the gas. The amount that drops out is not only the oil that was entrained by the gas, but also condensate. How much the latter is, must be calculated from the percentage line were the operating conditions are. This is difficult, because the actual phase envelope at such a moment can be also only calculated via approaches, because the possibility of taking a gas sample and analyze a chromatography up to C_{12} is under current conditions not possible.

The alternative is to calculate the losses of sealing oil at every compressor on the basis of the average losses of every compressor during one year. The data input for this method is quite low. There it can't be divided exactly how much oil has gone during the normal checks of the compressor units and how much is really left into the pipeline.

3.5.2. Standard correlations of gas composition

A common method for the determination of the hydrocarbon dewpoint in natural gas is an indirect method, which uses the measured composition of the gas up to C_5 and correlates the C_{6+} fraction. This part is according to Dustman et al.(36) divided into 47% C_6, 36% C_7 and 17% C_8. They identified problems with this correlation by comparison of the hydrocarbon dewpoint evaluated with the chilled mirror measurement and with this correlation, because the deviation between both values was up to 15°C. The result is shown in fig. 29.

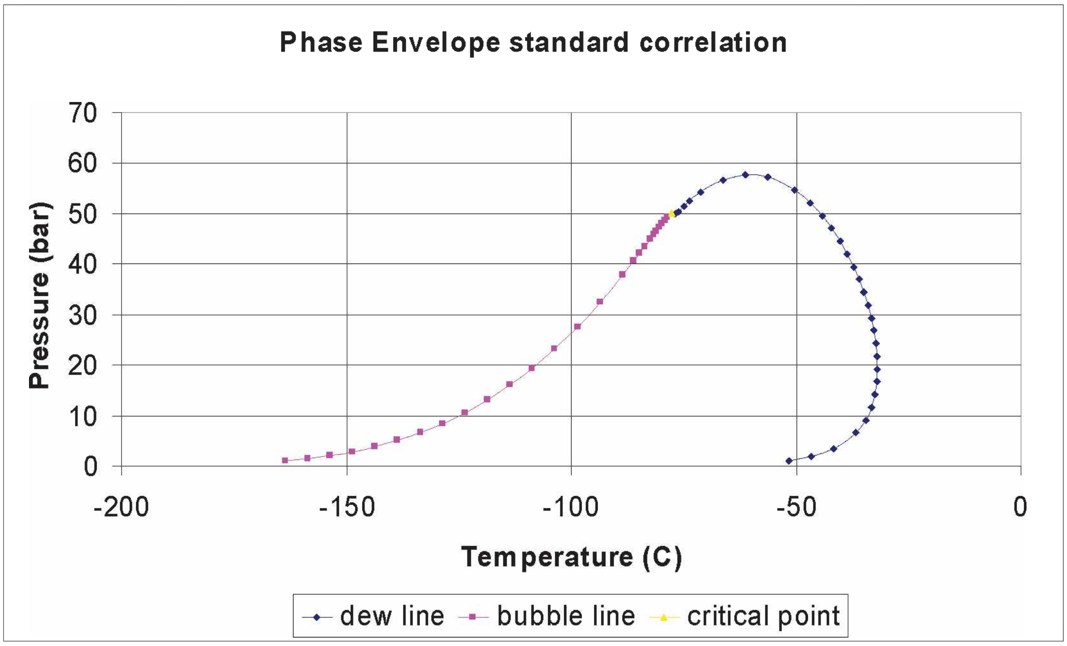

Figure 29: Phase diagram standard correlation

Another method that is often used is the extended gas chromatography. For this method the gas composition is measured up to C_{9+} and then the hydrocarbon dew point is calculated with an equation of state. It was possible to apply this technique for the actual problem, because a procedure, which was presented in the Erdöl, Erdgas, Kohle November 2004, was used to determine the heavier hydrocarbons in the gas. There an adsorption pipe is directly connected to an injection probe head (fig. 30). Thus the smallest amounts of heavy hydrocarbons can be measured without losses in a sampling box. Through this adsorption pipe a known amount of gas flew. Thus the amount of heavy hydrocarbons could be recalculated to a percentage value in the gas. To get the heavies again out of the pipe desorption process at a defined temperature was done and then the extracted hydrocarbons were measured with a gas chromatograph. The accuracy of this measurement was down in the parts per billion region and resulted in good consistency with the detected hydrocarbon dew point.

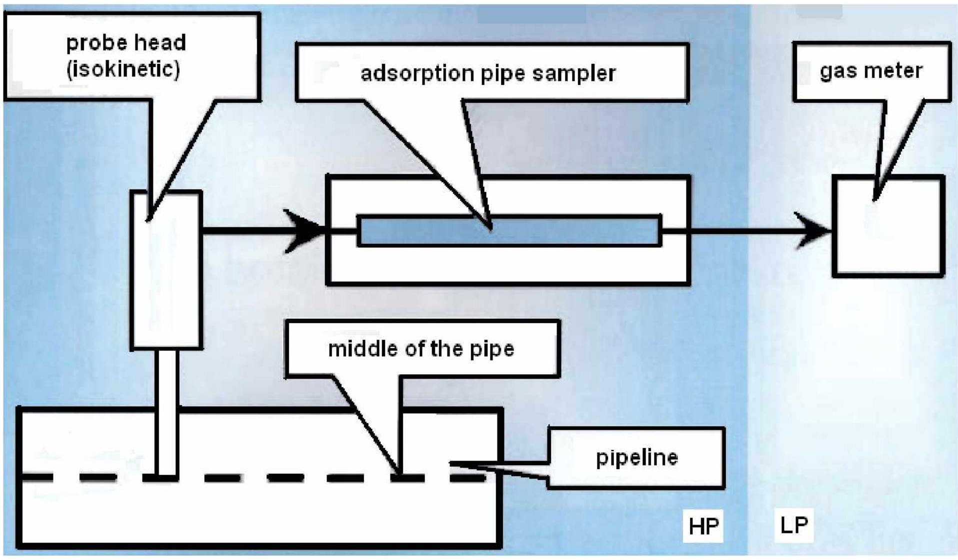

Figure 30: Sampling method for direct measurement in Weitendorf[35]

This procedure was used for this thesis in Weitendorf on 28th November 2007 to determine the composition of the C_{6+} fraction. For this case a probe head, which has reached to the middle of the gas stream, placed after the filter separator of the branching point of the Sol, was used to take the sample of the gas. Therefore the measured amount of 15 litres gas flowed through an adsorption pipe filled with activated charcoal. Additionally the water dewpoint and the hydrocarbon dewpoint were measured with the above described method of chilled mirror. There existed problems for the evaluation of the HC dewpoint, because at 61 bar the condensation on the mirror could not be identified with 100 % as condensate. For this reason the pressure was reduced for a further measurement and at 30 bar hydrocarbon condensate could be found. The ambient temperature was determined and also the temperature of the gas. Furthermore two dry and two wet samples of the gas were taken for the determination of the gas composition.

The results of the measurements are the displayed in tab. 7 and tab. 8:

water dewpoint	-13°C	at 61 bar
HC dewpoint	-13 °C	at 30 bar
gas temperature	26.6 °C	at 61 bar
ambient temperature	5 °C	

Table 7: Measured data

Component:	**mol %**
CO_2	0.1827
N_2	0.8012
CH_4	97.4380
C_2H_6	1.1012
C_3H_8	0.3455
$I\text{-}C_4H_{10}$	0.0494
$N\text{-}C_4H_{10}$	0.0555
$I\text{-}C_5H_{12}$	0.0102
$N\text{-}C_5H_{12}$	0.0073
C_6H_{14}	0.0056
C_7H_{16}	0.0021
C_8H_{18}	0.0010
C_9H_{20}	0.0001
mol-weight [kg/kmol]	16.4993
density [kg/m^3]	0.7375

Table 8: Measured composition

It was not possible to determine also the heavier hydrocarbons, because the sampling and measurement devices, which can be applied, are not accurate enough to receive trustable results in the ppm region.

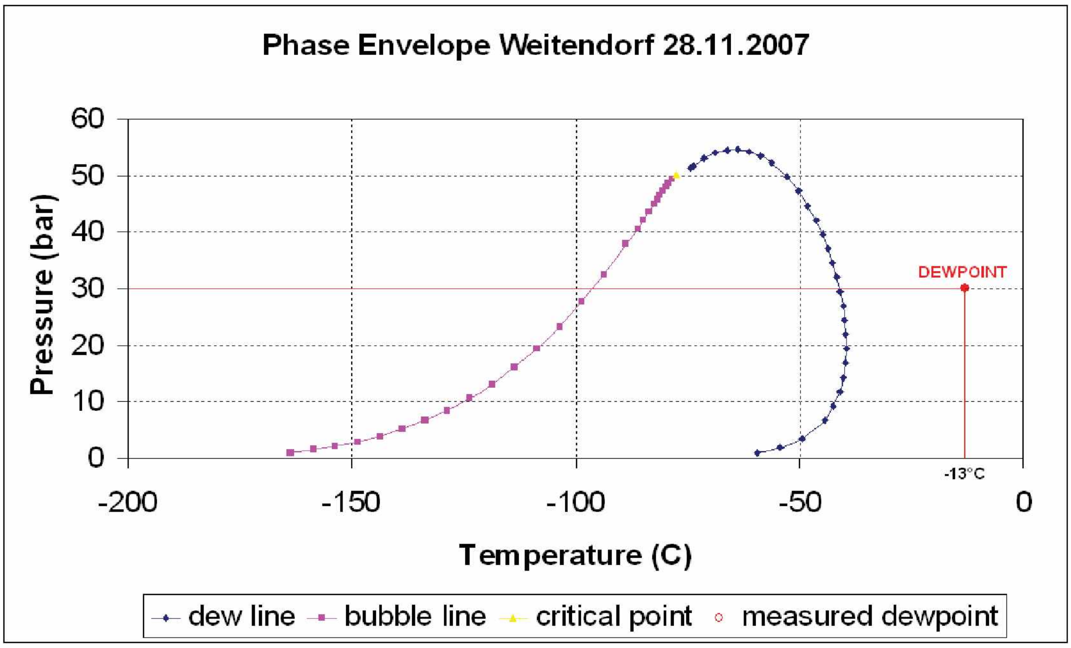

Figure 31: Phase diagram expanded measurement with measured dewpoint

The phase envelope is built with the analysis up to C9. It can be seen in fig. 31 that the measured value of the HC dewpoint is far away from the one built with Gas VLE. There are two possible explanations for this difference.

The first is that during the measurement the two dewpoints were close together. Therefore it is possible that the hydrocarbon dewpoint was confused with the water dewpoint. This is likely, if the dewpoint is as low as the calculation shows.

The other explanation is that there still exist heavier hydrocarbons in the gas, which would influence the calculation of the dewpoint significantly. Therefore it is necessary to model the possible composition of this part of the gas. The first method used, is to apply the normal standard correlation to the C_{10+} values. This leads to the result showed in figure 35. As it can be seen in fig 32 the hydrocarbon dewpoint is far away from measured results. Therefore this method is not appropriate.

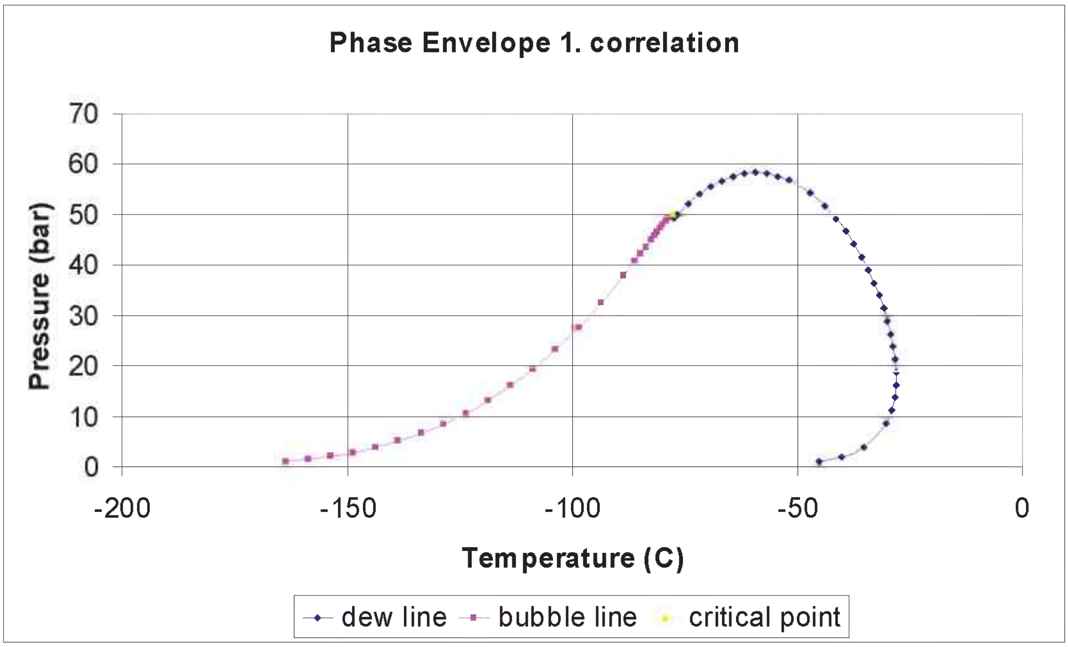

Figure 32: Phase diagram 1. correlation

The second model, which is applied, uses the same distribution of the heavier hydrocarbons as the model, which has been developed for the most likely scenario distribution.

However, this model now is over predicting the measured hydrocarbon dewpoint significantly (fig. 33). This can be on the one hand due to the effect of the hydrocarbon tail for the measurement, or that some additional hydrocarbons have already dropped out, that changed the composition of the heavier hydrocarbons and therefore the hydrocarbon dewpoint decreased.

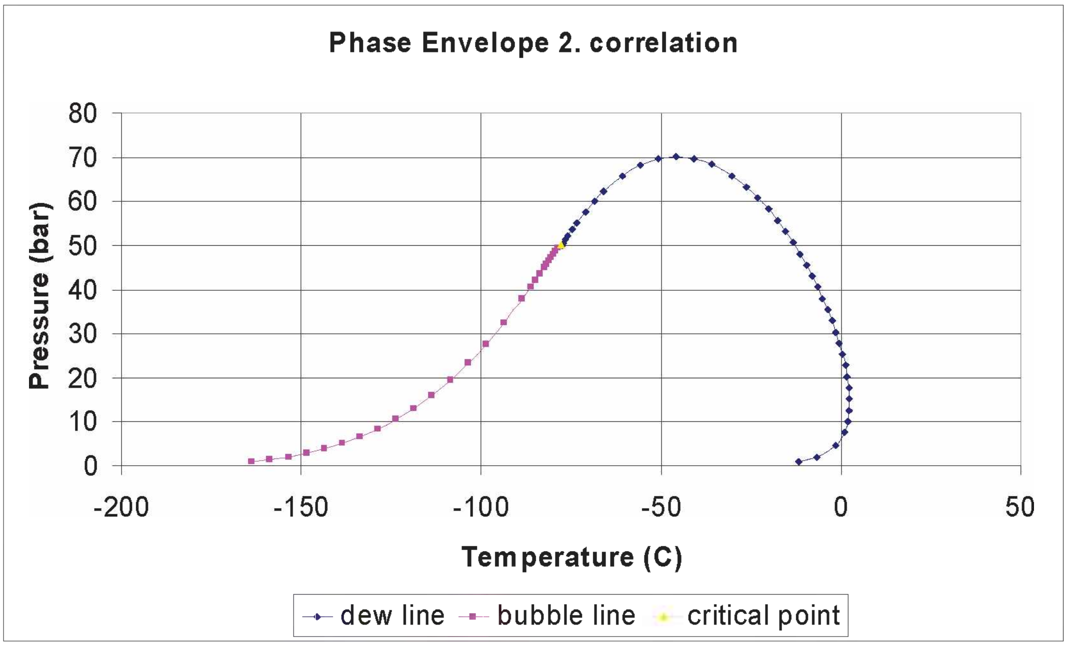

Figure 33: Phase diagram 2. correlation

Based on this analyses it can be said that the real phase diagram of the composition must lay in between the direct measurement and the second correlation for normal gas flow. At this point the influence of the lubricating oil from the compressor on the composition can be already neglected, because the resulting condensates are normally formed directly after the compressors. Only by reentrance into the gas they can have an influence, but directly at this branching system no condensates are built.

3.5.3. Liquids built due to pressure and temperature variation

The pressure downstream from branching systems is normally lower than upstream. The reduction is performed at this point. Regular decreases are between 5 and 10 bar. If we calculate the Joule-Thomson coefficient for a maximum temperature of 25°C, which is the minimum coefficient, then we get a result of 0.33 K/bar. For lower temperatures the coefficient increases till 0.4 K/bar.

Therefore the maximum temperature reduction at the delivery point can be 4°C. Further pressure decreases will lead to more temperature reduction. Thus it is possible that with both incidents at the same time the operating conditions reach the two phase area and additional fluid is created right after the delivery point. An additional contribution can be a lower temperature of the gas.

3.5.4. Maximum amount of condensates as aerosols at the branching point Weitendorf

Since the installation of the filter separator in Weitendorf one year ago the amount of fluid, which was found, had a total amount of 15 litres. The filter is able to remove 99.9% of the aerosols, which are large than 1 µm. Therefore the amount of liquid aerosols sized larger than this, which are able to pass the filter, is 0.015 litres. As it is shown before normally 80 percent of the aerosols are larger than one micrometer. Thus twenty percent are smaller and can also bypass the filter. The volume of these aerosols is 3.75 litres. Therefore it can be said that not more than 4 litres in one year are bypassing this filter. The rest of the liquid, which is found in the pipelines after the branching point, must be built through the reduction of the pressure and temperature in this system.

3.6. Glycol vapour pressure analysis

The aqueous mixture of TEG and DEG can have only entered the pipeline system during the flow of the gas through an absorber tower. There is normally installed a demister after the bubble trays to avoid glycol losses into the line, but during normal operating conditions it is possible that they are going through this due to the fact that some of the TEG becomes vaporized.

There are two possibilities why not only triethylene glycol is found in the sample but also DEG. The first is that the TEG was converted through thermal reduction into DEG and the other is that some DEG is transported from Russia to Austria via the transit pipelines, because in Austria DEG is not in use any longer, because its vapour pressure is higher and therefore more glycol would be lost into the line. Furthermore it would not decrease the water dewpoint of the gas as much as the TEG.

The vapour pressures of diethylene glycol were evaluated on the basis of the Ambrose Walton method. It uses the critical data of the substance and its acentric factor for the calculation.

The acentric factor is a parameter that shows how much like a sphere is the shape of the molecule of a substance. It is calculated with the following formula:

$$\omega = \frac{3}{7} * \frac{T_B}{T_C - T_B} * \log\left(\frac{p_C}{p_0}\right) - 1 \qquad (26)$$

ω…acentric factor

T_B…normal boiling temperature [K]

T_C…critical temperature [K]

p_C…critical pressure [bar]

p_0=1.013 bar

The equations of the Ambrose Walton method itself:

$$\ln\left(\frac{p}{p_C}\right) = f^{(0)} + \omega * f^{(1)} + \omega^2 * f^{(2)} \qquad (27)$$

$$f^{(0)} = \frac{-5.97616 * \tau + 1.29874 * \tau^{1.5} - 0.60394 * \tau^{2.5} - 1.06841 * \tau^{5}}{T_r} \tag{28}$$

$$f^{(1)} = \frac{-5.03365 * \tau + 1.11505 * \tau^{1.5} - 5.41217 * \tau^{2.5} - 7.46628 * \tau^{5}}{T_r} \tag{29}$$

$$f^{(2)} = \frac{-0.64771 * \tau + 2.41539 * \tau^{1.5} - 4.26979 * \tau^{2.5} + 3.25259 * \tau^{5}}{T_r} \tag{30}$$

$$T_r = \frac{T}{T_C} \tag{31}$$

$$\tau = 1 - T_r \tag{32}$$

T_r...reduced temperature

The values for diethylene glycol were taken from the nist chemistry web book and displayed in tab. 9.

This data leads to the amount of diethylene glycol, which can evaporate at a certain temperature and pressure. This is then the maximum amount of glycol that can be in gas phase and will flow with the sales gas into line. The results of the calculation are in Appendix A.

critical temperature **T_c**	753	[K]
critical pressure **p_c**	47.7	[bar]
boiling temperature at 1.013 bar **T_B**	515.15	[K]

Table 9: Triethylene glycol data

The uncertainty for this calculation was that diethylene glycol will be not used as 100 percent pure substance, but as a mixture of water and glycol due to the fact that the Ambrose Walton method was developed for pure substances.

The vapour pressures of triethylene glycol were evaluated by the Antoine equation, which can be used when the constants are known. The values for the calculation were delivered by the chemistry company DOW.

The Antoine constants for triethylene glycol are shown in tab. 10:

TEG weight %	A	B	C
0	7.959199	1663.545	227.575
50	7.922294	1671.501	228.031
70	7.878546	1681.363	228.237
80	7.837076	1697.006	228.769
90	7.726126	1728.047	229.823
95	7.620215	1806.257	236.227
97	7.495349	1841.522	238.048
98	7.404435	1881.474	240.666
99	7.211145	1926.114	242.799
99,5	7.042989	1970.802	242.865
100	7.472115	2022.898	152.573

Table 10: TEG glycol data

The Antoine equation is the following:

$$\log_{10}(p) = A - \frac{B}{(T+C)} \tag{33}$$

p… pressure [Torr]

T… temperature [°C]

Inserting the constants into the equation leads to the vapour pressure of TEG and the results can be found in Appendix A. The calculation of the vapour pressures leads to the information how much glycol can be in vapour phase at a certain pressure and temperature. Therefore it is possible to evaluate how much glycol starts to condense.

The worst case scenario for this case would be new glycol, which has a water part, which tends to be zero. The normal aqueous part of TEG in OMV dehydration units is below 2 %, but when new glycol is filled in this part decreases. Normally the absorber units have to be refilled during the start up process, because the regulators of the dehydration units have some failures in this period. Therefore the guaranteed value for the losses at the absorber tower, which is normally less than 6 kilogram per 1,000.000 standard cubic meters, are exceeded during this process. Then maximum losses can be up to 1300 litres in 3 days according to the engineers, which are responsible for the start up. The glycol dehydration units are not active during the year. Only when the water dewpoint increases above -6 °C, the absorber towers dry the gas. In the year 2007 the dehydration units were unusual often actuated. In the months August and October the glycol units were already activated in each case for one week.

The minimum amount of gas, which flows in three days in the TAG would be 26.7 million cubic meter gas and the maximum would be 101.1 million cubic meter. The worst case would be that a minimum of gas flows through the absorber towers, while they are started. This would mean that the 1300 litres would be dispersed in 26.7 million cubic meter gas. If this is calculated back to 1 million cubic meter gas, this would mean that in every million m^3 gas 48.7 litres glycol are dispersed. The vapour pressure in the worst case for a 99.5 % pure TEG would be dependent on the current total pressure far below this.

In the worst case scenario the gas would be cold, which means a temperature around ten degrees Celsius. The purity of the TEG would be high, as suggested here 99.5 % and also the total pressure would be high, so it is taken for the calculation as the highest possible with 70 bar. All these assumptions leads to a possible amount of glycol that stays in vapour phase with only 0.00201 litres per 1 million cubic meter gas.

Due to these facts the largest amount of TEG which can be taken for the analysis of the flow regime is 48.687 l/million m^3 gas.

The calculation how much diethylene glycol can condense is more complicate then evaluation of TEG, because it is not possible to say how much DEG is left in the gas after the transport. Therefore it is necessary to draw the conclusion that DEG will react in the same way as the TEG and in the worst case will drop out not more DEG than TEG.

Thus the maximum amount of aqueous glycol will not be more than 100 litres per 1 million cubic meters of gas.

3.7. Analysis of flow regime in the TAG

For the analysis of the flow regime the author used the method after Ben Asante, because this model was especially developed for the flow of transmission gas with only low liquid loads.

$$\varepsilon_L = \frac{v}{1+v} \tag{34}$$

$$v = \frac{u_{SL}}{u_{SG}} * \left\{ 1 + 10.4 * \mathrm{Re}_{SL}^{-0.363} * \left(\frac{\rho_L}{\rho_G} \right)^{0.5} \right\} \tag{35}$$

$$\mathrm{Re}_{SL} = \frac{\rho_L * v_L * d}{\eta} = \frac{v_L * d}{\upsilon} \tag{36}$$

The measured viscosity of the liquid, which consisted of condensate and lubrication oil, was the following:

v_L=83.438 mm^2/s and η= 72.333*10^{-3} Pas at 20°C

v_L=49.25 mm^2/s η= 42.402*10^{-3} Pas at 30°C

v_L=31.244 mm^2/s η= 26.697*10^{-3} Pas at 40°C

The density of the fluid was also determined:

ρ=866.9 kg/m^3 at 20°C

ρ=861 kg/m^3 at 30°C

ρ=854.5 kg/m^3 at 40°C

The values for the constant parameters of TEG were calculated by values, which were listed by the chemistry company DOW and evaluated with equation 37 and displayed in tab. 11 and fig. 34.

$$\eta = A * 10^{B*x} \qquad (37)$$

η…viscosity [cP]

x…weight % of TEG

Temp. [°F]	A	B
0	1.53010	2.9967E-2
50	1.09200	1.9348E-2
100	0.58916	1.5763E-2
150	0.37045	1.3481E-2
200	0.27371	1.1731E-2
250	0.18759	9.7064E-3
300	0.14026	8.1319E-3

Table 11: Triethylene glycol viscosity constants

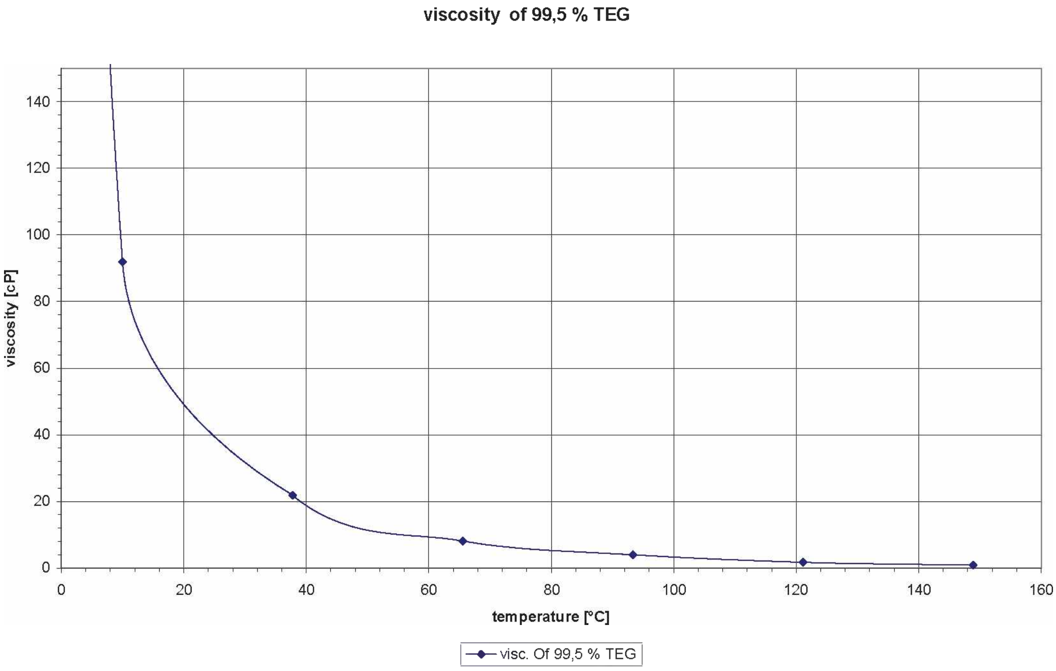

Figure 34: Viscosity of 99.5 % TEG

The viscosity is only slightly changing with varying water content of the TEG, thus the modification of the values are so small that they are negligible.

For the calculation of the velocity the diameter of the pipe and the amount of gas that is flowing through the pipe is necessary. Then the amount of liquid that flows at the maximum and with the most likely probability can be evaluated via the quality lines of the phase diagrams and additionally the glycol amount must be calculated.

The amount of gas that flows through the system is only measured in the TAG 1 and must be calculated back to all three pipelines. Due to the fact that the three pipes have very similar diameters it is possible to say that nearly one third of the amount is flowing through each pipe. The significant points of interest are the compressor stations and the offtake points along the pipeline. These are the places, where it is important to know, do I have fluid in the gas and in which flow regime is it.

$$A = \frac{d^2 * \pi}{4} \tag{38}$$

$$v_L = \frac{q_L}{A} \tag{39}$$

A...pipe area [m^2]

d...pipe diameter [m]

q_L...liquid amount [m^3/day]

v_L...fluid velocity [m/day]

Therefore the cross section in TAG 1 from Baumgarten to Grafendorf can be evaluated as 0.69 m^2 after Grafendorf to Wettmannstetten with 0.689 m^2 and behind Wettmanstetten to Ruden the area is calculated with 0.620 m^2. The pipe between Ruden and Arnoldstein has an area of 0.618 m^2.

The TAG 2 also consists of pipes with different diameters. Therefore the area from Baumgarten to Grafendorf is only 0.842 m^2 and afterwards till Arnoldstein 0.843 m^2.

The TAG Loop 2 (TAG 3) is built in one dimension over the whole length and hence the pipe area is 0.771 m^2.

The exact amount of fluid, which flows in the gas stream at every point, can not be determined, because the composition of gas changes all the time and therefore the amount of fluid. Furthermore the operation conditions are variable, which makes it impossible to determine the exact amount of fluid everywhere. Therefore it is necessary to say what the maximum liquid content of the gas would be and what the consequent flow regime is.

The sum of TEG and DEG is in the maximum case 100 litres per one million cubic meter gas. Lubrication oil is lost at maximum 20 000 litres per year, whereas the main portion does not go into the pipeline, but is changed during maintenance. Therefore only 20 % of this value can be taken for this calculation. This means 4000 litres in 4 billion cubic meter gas per year. When this is calculated back, we must add 1 litre per one million cubic meter gas as an average. However, the technicians at the compressor stations mean that for singular occasions also values of up to 50 litres per one million cubic meter gas can be reached. Out of the K-factor analysis we know that the maximum liquefiable part of the gas is 0.1 ppm, when we take the most likely composition. This means 100 litres per one million cubic meter gas. Hence the total amount of fluid in the worst case would be 250 litres/MMCM. The minimum gas amount that flows in the TAG is 26.5 million cubic meter per day.

This means for the calculation in Weitendorf an area that consists of the following parts:

TAG 1 Grafendorf to Wettmannstetten	0.689 m^2
TAG 2 Baumgarten to Grafendorf	0.842 m^2
TAG Loop 2 (TAG 3)	0.771 m^2
	ΣA=2.302 m^2

$$v_{L\_glycol} = \frac{\frac{0.1}{(24*3600)}}{2.302} = 0.00181 \ [\frac{m}{h}] = 5.003*10^{-7}[\frac{m}{\sec}]$$

$$v_{L\_condensate} = \frac{\frac{0.15}{(24*3600)}}{2.302} = 0.002715[\frac{m}{h}] = 7.54*10^{-7}[\frac{m}{\sec}]$$

Condensate plus lubrication oil:

η= 72.333*10^{-3} Pas

ρ=866.9 kg/m^3 at 20°C

DEG 20°C: viscosity: 38 mPas density: 1120 kg/m^3

TEG 20°C: viscosity: 49 mPas density: 1124 kg/m^3

average: viscosity: 43.5 mPas density: 1122 kg/m^3

$$\mathrm{Re}_{SL\_condensate} = \frac{866.9*7.54*10^{-7}*1.712}{72.333*10^{-3}} = 1.55*10^{-2}$$

$$\mathrm{Re}_{SLglycol} = \frac{1122*5.003*10^{-7}*1.712}{43.5*10^{-3}} = 2.21*10^{-2}$$

$$u_{SG} = \frac{q_G}{A} = \frac{111070.9}{2.302} = 13{,}4[\frac{m}{\sec}] \qquad v_L = u_{SL}$$

$$v_{condensate} = \frac{7.54*10^{-7}}{13.4}*\left\{1+10.4*(1.55*10^{-2})^{-0.363}*\left(\frac{866.9}{0.7375}\right)^{0.5}\right\} = 9.11*10^{-5}$$

$$\varepsilon_{L\_condensate} = \frac{9.11*10^{-5}}{(1+9.11*10^{-5})} = 9.11*10^{-5}$$

$$v_{glycol} = \frac{5.003*10^{-7}}{13.4}*\left\{1+10.4*(2.21*10^{-2})^{-0.363}*\left(\frac{1122}{0.7375}\right)^{0.5}\right\} = 6.045*10^{-5}$$

$$\varepsilon_{L\_glycol} = \frac{6.045*10^{-5}}{(1+6.045*10^{-5})} = 6.046*10^{-5}$$

$$\varepsilon_{L\_total} = \varepsilon_{L\_condensate} + \varepsilon_{L\_glycol} = 9.11*10^{-5} + 6.046*10^{-5} = 1.516*10^{-4}$$

$$\varepsilon_{L\_total} < 0.005$$

For the calculation the maximum amounts of liquid were taken and the minimum amount of gas. The evaluation was done for the TAG mainstream, but it is also valid for the branching arms, because the amount of aerosols, which flow into a branching arm, is proportional to the gas amount. The viscosity and density values were taken at the average temperature of 20°C.

3.8. Vanishing of liquid

The liquids and accumulations in the pipeline systems are not constant. Therefore it can happen that at one point sometimes fluid can be found and the next time everything is dry. The causes for these events are diverse.

One is that the operating conditions are changing when the surrounding temperature varies, compressor stations go offline or something else happens, which changes either the temperature or the pressure of the gas.

Another reason is that also the composition of the sales gas is not constant. There exist only guideline values, which restrict minimum and maximum values of the single components. This is critical for the heavy hydrocarbons, where normally only the total amount of the C_{6+} values is regulated, while it is of the same importance, how they are distributed. These distributions are of such sensibility that variations in the ppm region and below are enough to make the difference between the possibility that liquids build or not.

Due to the fact that during the start up phase also triethylene glycol is lost into the pipeline, while in most times of the year no glycol drying is necessary, also the amount of glycol in the system is permanently changing. Furthermore the amount of sealing oil, which gets lost at the compressors, is not always the same. During normal operation the losses are nearly negligible, but when failures occur the amount can rise to 55 litres per million cubic meter gas in a short period.

When liquid really condenses, it can travel around 700 meters, before accumulation starts. On the one hand these puddles of fluids can re-vaporise into the gas phase when the composition or the operating conditions change, because then the vapour pressure above the liquid also changes. On the other hand the fluid at the bottom of the pipe is entrained because of the high velocity of the gas. This means values around 15 m/s.

3.9. Technical Consequences and possible solutions

The conclusion out of the analysis made is that in the TAG pipeline systems not only single phase flow occurs, but also mist flow with aerosols is possible. The exact points, when the transition happens cannot be predicted properly due the continuous change of the operating conditions.

A result of this research is that parameters were find, which contribute to the affinity of the gas to build liquids. One of it is the amount of lost sealing oil at the compressor stations. To minimize this parameter the possibility of changing the sealings from oil based to dry ones, should be taken into consideration. This would decrease the amount of heavy hydrocarbons and can therefore reduce the dewpoint of the gas. Thus the condensation of hydrocarbons from the gas would be less and also the amounts of the sealing oil would be less. It would be advisable to monitor at the compressor stations, how much oil is left to the pipeline and how much is changed at the normal inspection, before such a project can be done.

The glycol, which is also part of the fluids, comes on the one hand from the import gas itself and on the other hand from the drying units in Baumgarten. The first point can’t be changed; hence an analysis for the improvement of the drying unit operation should be made. How much glycol gets lost by carry over to the system and is it possible to reduce this by the change of the start up operation.

It is clear that the dewpoint of the gas changes with pressure, temperature and the influence of the heavy hydrocarbons. Although the gas can be clean of fluids at the delivery point, the possibility of liquid generation somewhere behind this point can’t be excluded. For this reason it must be suggested that sensible customers protect their equipment by their own separation systems.

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5. Appendix A

temperature [K]	temp [°C]	Amount Glycol [l]				
		at 30 bar	at 40 bar	at 50 bar	at 60 bar	at 70 bar
263,15	-10.00	0.00008	0.00006	0.00005	0.00004	0.00004
273,15	0.00	0.00072	0.00054	0.00043	0.00036	0.00031
283,15	10.00	0.00469	0.00352	0.00281	0.00234	0.00201
293,15	20.00	0.02467	0.01850	0.01480	0.01234	0.01057
303,15	30.00	0.10820	0.08115	0.06492	0.05410	0.04637
313,15	40.00	0.40701	0.30526	0.24420	0.20350	0.17443
323,15	50.00	1.34	1.01	0.81	0.67	0.58
333,15	60.00	3.96	2.97	2.38	1.98	1.70
343,15	70.00	10.60	7.95	6.36	5.30	4.54
353,15	80.00	26.08	19.56	15.65	13.04	11.18
363,15	90.00	59.54	44.66	35.73	29.77	25.52
373,15	100.00	127.36	95.52	76.41	63.68	54.58

Table 12: Maximum amount of vap. triethylene glycol in litre per 1 mill. m^3 gas

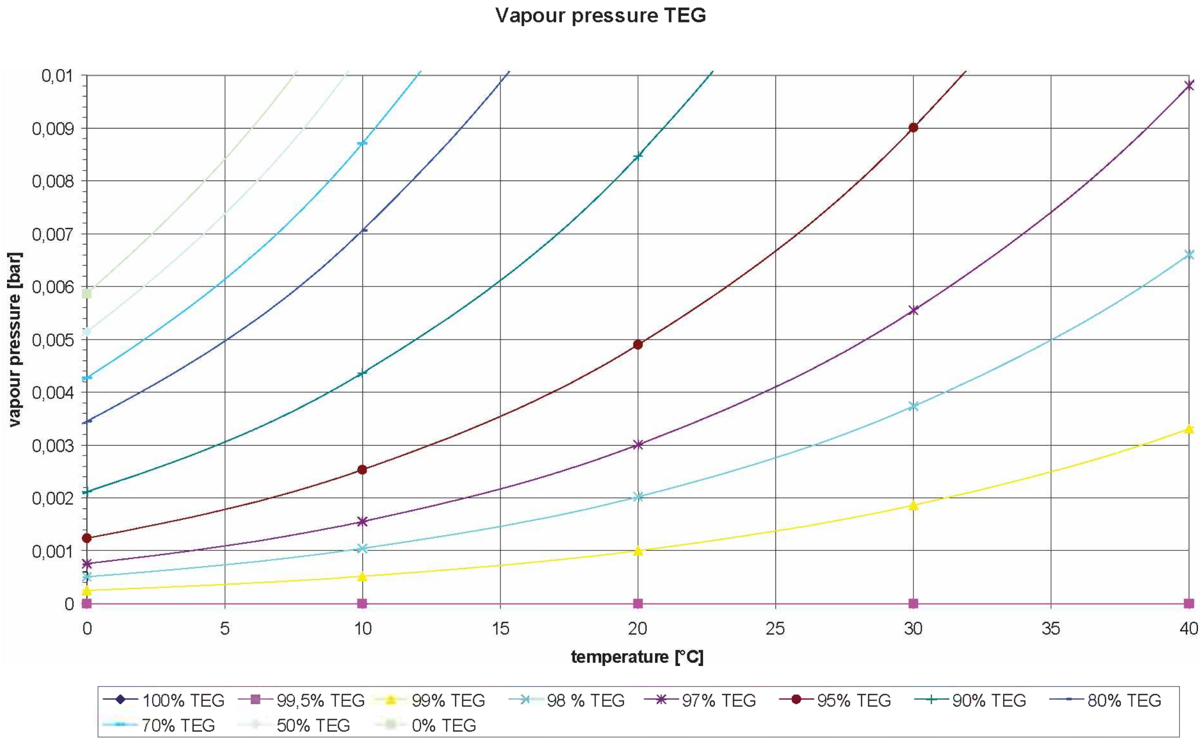

Figure 35: Calc. vapour pressure of TEG

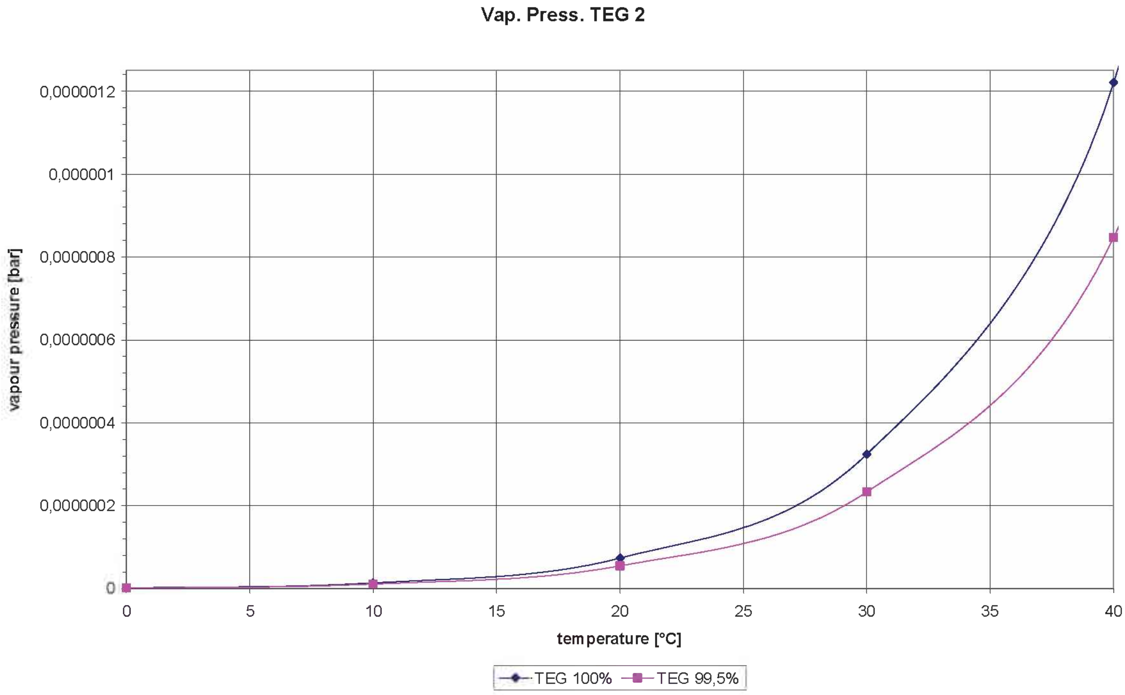

Figure 36: Calc. vapour pressure of TEG 2

temperature [K]	temp [°C]	at 30 bar	at 40 bar	at 50 bar	at 60 bar	at 70 bar
263.15	-10	0.1007	0.0756	0.0604	0.0504	0.0432
268.15	-5	0.1924	0.1443	0.1154	0.0962	0.0825
273.15	0	0.3573	0.2680	0.2144	0.1787	0.1531
278.15	5	0.6464	0.4848	0.3879	0.3232	0.2770
283.15	10	1.1407	0.8555	0.6844	0.5704	0.4889
288.15	15	1.9663	1.4747	1.1798	0.9832	0.8427
293.15	20	3.3152	2.4864	1.9891	1.6576	1.4208
298.15	25	5.4734	4.1050	3.2840	2.7367	2.3457
303.15	30	8.8590	6.6442	5.3154	4.4295	3.7967
308.15	35	14.0715	10.5536	8.4429	7.0357	6.0306
313.15	40	21.9558	16.4668	13.1735	10.9779	9.4096
318.15	45	33.6828	25.2621	20.2097	16.8414	14.4355
323.15	50	50.8497	38.1373	30.5098	25.4248	21.7927
328.15	55	75.6023	56.7017	45.3614	37.8012	32.4010
333.15	60	110.7837	83.0878	66.4702	55.3918	47.4787
338.15	65	160.109	120.0819	96.0655	80.0546	68.6182

		2				
343.15	70	228.3731	171.2798	137.0238	114.1865	97.8742
348.15	75	321.6862	241.2646	193.0117	160.8431	137.8655
353.15	80	447.7485	335.8113	268.6490	223.8742	191.8922
358.15	85	616.1556	462.1166	369.6933	308.0777	264.0666
363.15	90	838.7415	629.0560	503.2447	419.3706	359.4605
368.15	95	1129.955	847.4664	677.9730	564.9775	484.2664

Table 13: Maximum amount of vap. diethylene glycol in litre

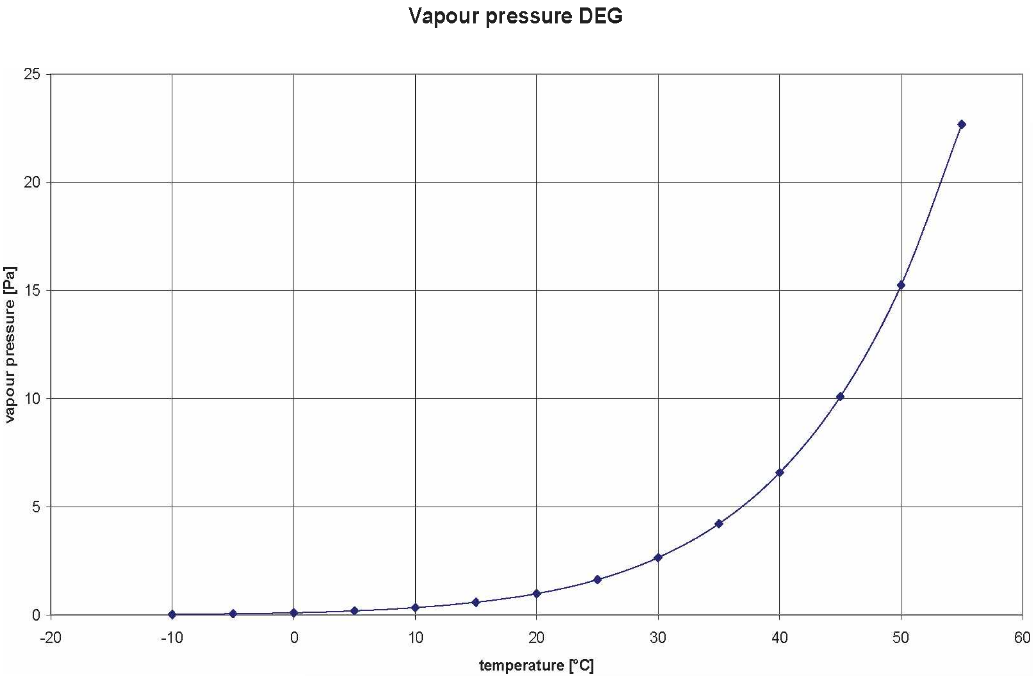

Figure 37: Calc. vapour pressure of DEG

TAG1

	pres. min [bar]	pres. max [bar]	temp. min [°C]	temp. max [°C]
Baumgarten	51.64	69.18		
Eggendorf	49.27	67.87		
Eggend. EVN	45.53	56.52		
Grafend. vor K.	42.52	64.87	8.88	18.49

Grafend. n. K.	54.43	70.31		
Graf. BEGAS	41.62	60.01		
St. Marg.	52.53	69.01		
St.Marg. STGW	17.97	66.76		
Weitendorf				
Weitd. STGW	46.12	59.31		
Weitd. SOL	49.95	66.72		
Sulm.-Gr.	49.87	67.77		
Sulm.-Gr. STGW	47.94	65.54		
Ettendorf	45.63	66.66		
Ettend. KELAG	7.98	62.48		
Ruden vor K.	42.17	65.49		
Ruden nach K.	58.7	69.82		
Waisenberg	46.05	70.89		
Waisenb. KELAG	44.9	67.29		
Ebenthal	58.48	68.71	15.72	25.23
Eben. KELAG	58.48	66.66		
Finkenstein	54.77	67.59		
Fink. KELAG	29.15	64.37		
Arnoldstein				

TAG2

	pres. min [bar]	pres. max [bar]	temp. min [°C]	temp. max [°C]
Baumgarten	51.64	69.18		
Eggendorf	48.69	67.37		
Eggend. EVN				
Grafend. vor K.	42.59	65		
Grafend. n. K.	54.43	70.31		
Graf. BEGAS				
St. Marg.	0	69.49		
St.Marg. STGW				
Weitendorf	51.33	68.58		

Weitd. STGW				
Weitd. SOL				
Sulm.-Gr.				
Sulm.-Gr. STGW				
Ettendorf				
Ettend. KELAG				
Ruden vor K.				
Ruden nach K.	58.76	69.93		
Waisenberg	58.82	69.27		
Waisenb. KELAG				
Ebenthal	54.88	69.03		
Eben. KELAG				
Finkenstein	56.13	67.63		
Fink. KELAG				
Arnoldstein	54.08	66.14		

TAG3

	pres. min [bar]	pres. max [bar]	temp. min [°C]	temp. max [°C]
Baumgarten	51.64	69.18		
Eggendorf	48.59	67.35	15.88	26.12
Eggend. EVN				
Grafend. vor K.	0.02	65.11		
Grafend. n. K.	54.43	70.31		
Graf. BEGAS				
St. Marg.	1.64	69.2	12.17	29.93
St.Marg. STGW				
Weitendorf	52.07	71.61		
Weitd. STGW				
Weitd. SOL				
Sulm.-Gr.				
Sulm.-Gr. STGW				

Ettendorf				
Ettend. KELAG				
Ruden vor K.				
Ruden nach K.	58.79	70.36		
Waisenberg	58.63	69.58	15.19	39.72
Waisenb. KELAG				
Ebenthal	58.37	73.11		
Eben. KELAG				
Finkenstein	0	65.01	6.93	42.57
Fink. KELAG				
Arnoldstein			11.72	19.11

Table 14: Minimum and maximum data for the offtake points and compressor station