COVER BLOW-OFF RESISTANCE OF REINFORCED THERMOPLASTIC PIPES FOR GAS SERVICE

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ABSTRACT
A mathematical model was set up to assess the equilibrium gas pressure in the annulus of the reinforcement layer of an RTP pipe. This is done by using the theory of gas permeation, ruled by Fick's Law and the theory for a temperature gradient over the pipe wall, ruled by Fourier's law. The model allows calculating the influence of different liner pipe materials and temperature gradients inside the multilayer pipe on this parameter. The equilibrium gas pressure in the annulus was compared with the cover blow-off threshold pressure of a commercial RTP pipe. Changing the liner pipe material would result in a limiting factor of the maximum allowable operating pressure of the RTP system itself and not the cover blow-off resistance.

INTRODUCTION
Reinforced thermoplastic pipe (RTP) is a flexible pipe that can be used as an alternative for steel pipe in high-pressure gas applications (1,2). In Figure 1 a typical commercial RTP pipe is shown. Such a RTP pipe consists of three layers:

1. a thermoplastic liner pipe containing the gas,
2. a reinforcement layer providing the strength and
3. a HDPE cover layer to protect the pipe from mechanical damage and UV-radiation.

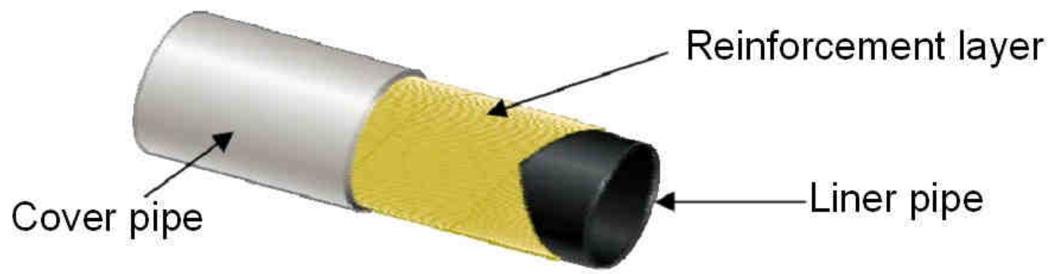


Figure 1. Typical RTP pipe (courtesy of Pipelife).

The liner pipe can be made from any kind of polymeric material, but PE is mostly used. The reinforcement layer can be made from steel wires or synthetic fibres such as aramid embedded in a PE matrix. Between these wires or fibres in the reinforcement layer an empty annular space exists, as there is no bonding between the wires or fibres and the matrix. Gas can permeate through the polymeric liner pipe and accumulate in this annulus. If the pressure in the annulus rises above a certain threshold value, blistering of the cover pipe occurs. This will eventually lead to rupture of the cover layer. This process is called "cover blow-off". It will not cause immediate pipe failure, but the reinforcement layer is now exposed to the environment which might compromise its long-term integrity.

The equilibrium gas pressure which builds up in the annulus of the reinforcement layer (and thus the cover blow-off resistance) is determined by the operating pressure, the permeability of the liner and cover pipe and the dimensions of the pipe (1-3). If a temperature gradient is present, the equilibrium gas pressure is also dependent upon the temperature inside and outside the pipe material and the thermal conductivity of each layer.

The goal of this work is to set up a mathematical model which describes the influence of the various parameters and predicts the consequence of a change in liner pipe material. This paper describes the theory of permeation and permeation in the presence of a temperature gradient, followed by a case study where the liner pipe is changed.

PERMEABILITY

If the temperature inside the pipe is equal to the temperature outside the pipe, the equilibrium gas pressure in the annulus of the reinforcement layer is only dependent upon the dimensions of the pipe and the rate of gas permeation at constant temperature. First, the gas permeation will be discussed. Thereafter, an equation to calculate the gas pressure in the annulus shall be given.

Gas permeation is ruled by Fick's Law:

$$J_m = -D \cdot \frac{\partial c}{\partial x} \qquad [1]$$

where:

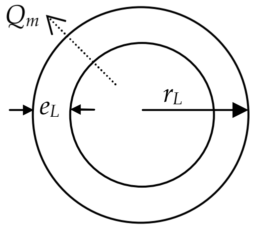
J_m	mass flux ($mol \cdot m^{-2} \cdot s^{-1}$)
D	diffusion coefficient ($m^2 \cdot s^{-1}$)
∂c	concentration difference ($mol \cdot m^{-3}$)
∂x	distance (m)

At steady state conditions the number of moles entering the pipe wall is equal to the number of moles leaving the pipe wall. Furthermore, it can be assumed that the concentrations inside and outside the pipe are constant in time. Using this information equation [1] can be rewritten for a cylindrical pipe to (4):

$$\Delta c = \frac{Q_m \cdot \ln\left(\frac{r_L}{r_L - e_L}\right)}{2 \cdot \pi \cdot L \cdot D} \qquad [2]$$

where:

Δc	concentration difference ($ml \cdot ml^{-1}$)
Q_V	volume of permeated gas ($m^3 \cdot s^{-1}$)
r_L	outer radius of the liner pipe (mm)
e_L	wall thickness of the liner pipe (mm)
L	length of the pipe (m)



In this equation a liner pipe is used, but the equation will be identical for a cover pipe.

Next, a conversion from concentration to gas pressure is made. The concentration of dissolved gas in the liner pipe material is linked to the pressure by Henry's law (5,6):

$$p = \frac{1}{S} \cdot c \qquad [3]$$

where:

p partial pressure (bara)

S solubility ($bara^{-1}$)

The pressure is given in absolute pressure (bara), so with respect to complete vacuum.
The diffusion coefficient (*D*) is linked to the permeability coefficient (P_C) according to (7, 8):

$$P_C = D \cdot S \qquad [4]$$

EXACT EQUATION

Combining equations [2], [3] and [4] results in an equation for the permeability coefficient for a liner pipe:

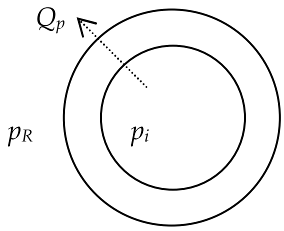
$$P_C = \frac{Q_P \cdot \ln\left(\frac{r_L}{r_L - e_L}\right)}{2 \cdot \pi \cdot L \cdot \Delta p} \qquad [5]$$

where:

P_C permeability coefficient ($ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$)

Q_P flow of permeated gas ($ml\ day^{-1}$)

Δp difference in partial pressure (bara)



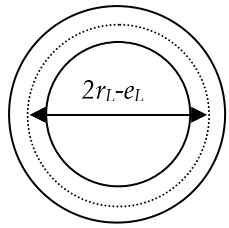
APPROXIMATE EQUATION

There was discussion in the past regarding which diameter should be used to calculate the permeability coefficient of pipes. Some laboratories used the outer diameter, whilst others favoured the inner diameter. The median diameter is used in a publication of Scholten and Wolters (9). Using the exact equation [5], the approximate equation of Scholten and Wolters can be verified. This approximate equation is given in equation [6], after rewriting it for a liner pipe to compare it with the exact equation.

$$P_C = \frac{Q_P \cdot e_L}{A_L \cdot \Delta p} = \frac{Q_P \cdot e_L}{(2 \cdot r_L - e_L) \cdot \pi \cdot L \cdot \Delta p} \qquad [6]$$

where:

A_L surface area of the liner pipe



Is this approximate equation [6] comparable to the exact equation [5]? In other words, what is the difference between the left hand side of equation [7] and the right hand side?

$$\frac{1}{2}\cdot\ln\left(\frac{r_L}{r_L-e_L}\right)\stackrel{?}{=}\frac{e_L}{(2\cdot r_L-e_L)} \qquad [7]$$

The difference between these two formulas is given in Table 1 for some standard SDR classes. This shows that the approximation by Scholten and Wolters differs only slightly from the exact equation and that their approximation was therefore justified. The difference becomes smaller at larger SDRs. For further calculations the exact equation will be used.

Table 1. Comparison between the exact equation [5] and the approximate equation [6].

SDR	Exact (left side equation [7])	Approximation (right side equation [7])	Difference (%)
6	0,2027	0,2000	1,35
11	0,1003	0,1000	0,33
17.6	0,0603	0,0602	0,12
33	0,0313	0,0313	0,03
41	0,0250	0,0250	0,02

PRESSURE IN THE REINFORCEMENT LAYER

To assess the resistance of a pipe against cover blow-off the equilibrium gas pressure in the annulus of the reinforcement layer should be compared to the threshold value at which cover blow-off occurs.

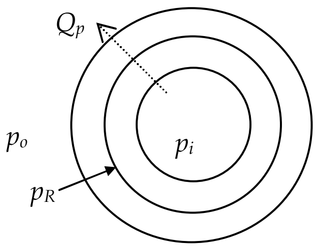
To calculate the equilibrium gas pressure, equation [5] is used. To simplify further calculations the permeation resistance (R_P) is introduced:

$$R_P=\frac{\ln\left(\frac{r}{r-e}\right)}{2\cdot\pi\cdot L\cdot P_C} \qquad [8]$$

At a steady state, the flow of permeated gas through the entire pipe wall (liner, reinforcement layer and cover) is identical, since no gas is consumed or produced inside the pipe. Therefore, using equations [5] and [8], the following permeation balance applies:

$$Q_P=\frac{1}{R_{PL}}(p_i-p_R)=\frac{1}{R_{PC}}(p_R-p_o) \qquad [9]$$

where:



- R_{PL} permeation resistance of the liner (bara·day ml^{-1})
- R_{PC} permeation resistance of the cover (bara·day ml^{-1})
- p_i pressure inside the pipe (bara)
- p_R pressure in the reinforcement layer (bara)
- p_o pressure outside the pipe (bara)

The permeation resistance of the reinforcement layer itself is negligible compared to that of the cover and the liner pipe. The partial pressure of methane outside the pipe is normally 0 bara, because no methane is expected there.

From equation [9] it therefore follows that:

$$p_R = p_i \cdot \frac{R_{PC}}{R_{PL} + R_{PC}} \qquad [10]$$

This means that the pressure at the reinforcement layer is dependent upon the pressure inside the pipe and the permeation resistance of the liner and the cover. A high pressure inside the pipe will result in a high pressure in the annulus of the reinforcement layer. Similarly, a high permeation coefficient (a low permeation resistance) of the liner will result in a high pressure in the reinforcement layer.

TEMPERATURE GRADIENT OVER THE PIPE WALL

If there is a difference between the temperature inside the pipe and outside the pipe, the temperature gradient should be taken into account. Because the permeability is dependent upon the temperature, the temperature at every location in the pipe should be known.

Calculating the temperature gradient starts with Fourier's law which describes the transfer of thermal energy:

$$J_T = -\lambda \cdot \frac{\partial T}{\partial x} \qquad [11]$$

where:

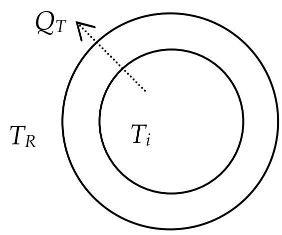
- J_T heat flux ($J \cdot m^{-2} \cdot s^{-1}$)
- λ heat conductivity ($J\ s^{-1} \cdot m^{-1} \cdot K^{-1}$)
- ∂T temperature difference (K)
- ∂x distance (m)

The steady-state temperature difference over a cylinder wall, such as the liner pipe, can be calculated in the same way as the concentration difference (equation [2]). The temperature difference is therefore given by (4):

$$T_i - T_R = \frac{\ln\left(\frac{r_L}{r_L - e_L}\right)}{2 \cdot \pi \cdot L \cdot \lambda_L} \cdot Q_T \qquad [12]$$

where:

- T_i temperature inside the pipe (°C)
- T_R temperature at the reinforcement layer (°C)
- λ_L heat conductivity of the liner ($J\ s^{-1} \cdot m^{-1} \cdot K^{-1}$)
- Q_T heat flow through the pipe wall ($J\ s^{-1}$)

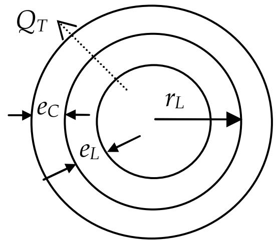


The temperature difference over the cover is calculated in a similar way. Such as the flow of permeated gas, the heat flow is constant through all the layers. From this the thermal balance is as follows:

$$Q_T = (T_i - T_R) \cdot \frac{2 \cdot \pi \cdot \lambda_L \cdot L}{\ln\left(\frac{r_L}{r_L - e_L}\right)} = (T_R - T_o) \cdot \frac{2 \cdot \pi \cdot \lambda_C \cdot L}{\ln\left(\frac{r_L + e_C}{r_L}\right)} \qquad [13]$$

where:

T_o	temperature outside the pipe (°C)
e_C	wall thickness of the cover (mm)
λ_C	heat conductivity of the cover (J $s^{-1} \cdot m^{-1} \cdot K^{-1}$)



In equation [13], the first part is the heat flow through the liner pipe and the second part is the heat flow through the cover pipe. This equation can now be used to calculate the temperature in the reinforcement layer by writing T_R explicit. This can be placed back into equation [13] which results in:

$$Q_T = \frac{2 \cdot \pi \cdot L \cdot \lambda_C \cdot \lambda_L}{\lambda_L \cdot \ln\left(\frac{r_L + e_C}{r_L}\right) + \lambda_C \cdot \ln\left(\frac{r_L}{r_L - e_L}\right)} (T_i - T_o) \qquad [14]$$

The heat flow calculated with this equation can now be used to calculate the temperature at every location in the RTP pipe.

DISCRETISATION

In order to determine the temperature at every location, the liner and cover pipe are divided in small layers. The temperature in these layers is assumed constant, so subsequently the permeation resistance (R_P) can be calculated for each layer.

The temperature in each layer is dependent upon the temperature of the previous layer, the heat conductivity and the total heat flow. Equation [12] gives the temperature at two positions and equation [14] gives the heat flow. Combining these equations results in the temperature of layers *j* of the liner pipe and *k* of the cover pipe, according to:

$$T_j = T_{j-1} - \frac{\ln\left(\frac{r_j}{r_j - e_j}\right)}{2 \cdot \pi \cdot \lambda_L \cdot L} \cdot Q_T = T_{j-1} - \frac{\lambda_C \cdot \ln\left(\frac{r_j}{r_j - e_j}\right)}{\lambda_L \cdot \ln\left(\frac{r_L + e_C}{r_L}\right) + \lambda_C \cdot \ln\left(\frac{r_L}{r_L - e_L}\right)} (T_i - T_o) \qquad [15a]$$

for the liner and

$$T_k = T_{k-1} - \frac{\ln\left(\frac{r_k}{r_k - e_k}\right)}{2 \cdot \pi \cdot \lambda_C \cdot L} \cdot Q_T = T_{k-1} - \frac{\lambda_L \cdot \ln\left(\frac{r_k}{r_k - e_k}\right)}{\lambda_L \cdot \ln\left(\frac{r_L + e_C}{r_L}\right) + \lambda_C \cdot \ln\left(\frac{r_L}{r_L - e_L}\right)} (T_i - T_o) \qquad [15b]$$

for the cover layer.

PERMEABILITY AT A TEMPERATURE GRADIENT

The temperature of each layer can be used to calculate the permeability coefficient. The permeability is actually strongly temperature dependent (6), according to:

$$P_C = P_{C0} \cdot \exp\left(-\frac{E_P}{R \cdot T} \right) \qquad [16]$$

where:

- P_{C0} normalized permeation coefficient (ml·mm·m^{-2}·bara^{-1}·day^{-1})
- E_P activation energy for permeation (kJ·mol^{-1})
- R gas constant (kJ·mol^{-1}·K^{-1})
- T absolute temperature (K)

The permeability coefficient is inversely proportional to the permeation resistance according to equation [8]. By combining this equation with equation [16], the permeation resistance can be written as a function of temperature. The temperature is calculated in each layer in equation [15a] for the liner pipe and equation [15b] for the cover pipe. The permeation resistance of each layer can be added together, similar to the resistors in an electrical series circuit. The total permeation resistance of the layer pipe and the cover pipe can be inserted in equation [10], which results in the pressure in the reinforcement layer.

This is given in the equation below where all of this is combined.

$$p_R = p_i \cdot \frac{\sum_{k=0}^{m} \left[\frac{\ln\left(\frac{r_k}{r_k - e_k} \right)}{2 \cdot \pi \cdot L \cdot P_{C0C}} \cdot \exp\left(\frac{E_P}{R \cdot T_k} \right) \right]}{\sum_{j=0}^{n} \left[\frac{\ln\left(\frac{r_j}{r_j - e_j} \right)}{2 \cdot \pi \cdot L \cdot P_{C0C}} \cdot \exp\left(\frac{E_P}{R \cdot T_j} \right) \right] + \sum_{k=0}^{m} \left[\frac{\ln\left(\frac{r_k}{r_k - e_k} \right)}{2 \cdot \pi \cdot L \cdot P_{C0C}} \cdot \exp\left(\frac{E_P}{R \cdot T_k} \right) \right]} \qquad [17]$$

Similar to equation [10], a high pressure inside the pipe or a low permeation resistance will result in a high pressure in the annulus of the reinforcement layer. Only this time the permeation resistance is written as the sum of all small layers where each layer has its own temperature and thus permeability.

CASE STUDY

The equilibrium gas pressure which builds up in the annulus of the reinforcement layer can be calculated using equations [15] and [17]. For this calculation, several parameters are needed:

1. the temperature and pressure inside and outside the pipe;
2. the dimensions of the pipe;
3. the heat conductivity of the liner and the cover pipe;
4. the permeability coefficient at a certain temperature of the liner and cover pipe and;
5. the activation energy for permeation of the liner and cover pipe.

The data for heat conductivity, permeability coefficient and activation energy for permeation can be measured (9), or found in the literature (10,11). Due to the inhomogeneous structure of the reinforcement layer, the thickness of the actual cover pipe cannot be measured exactly. Therefore the "effective cover thickness" is introduced. This thickness can be calculated using equation [5]. The permeability coefficient (P_C) of the cover pipe material and the flow of permeated gas (Q_P) for the pressurised cover pipe should therefore be measured.

In the first version of a commercial RTP pipe the liner and cover pipe were made from the same PE100 material. The allowable methane gas pressure inside the RTP pipe at a certain temperature depends upon the hydrostatic strength and the pressure in the reinforcement layer. Using additional experiments, the critical pressure in the reinforcement layer for cover blow-off is determined.
The described mathematical model is used to calculate the allowable operating pressures inside the RTP pipe at various temperatures, including a safety factor of 1.2 (see Figure 2). This means that the resulting pressures are the pressures at which the cover pipe will neither blister nor rupture. The temperature outside the pipe is assumed constant at 20 °C or 68 °F.
The hydrostatic strength of this commercial RTP pipe is also calculated for 50 years at 20 °C (68 °F) and 65 °C (149 °F) using the 2-parameter model according to ISO 9080 (12). These two values (including a safety factor of 2) are also given in Figure 2. The function of the dotted line between these points is to guide the eye: there is no calculation involved.

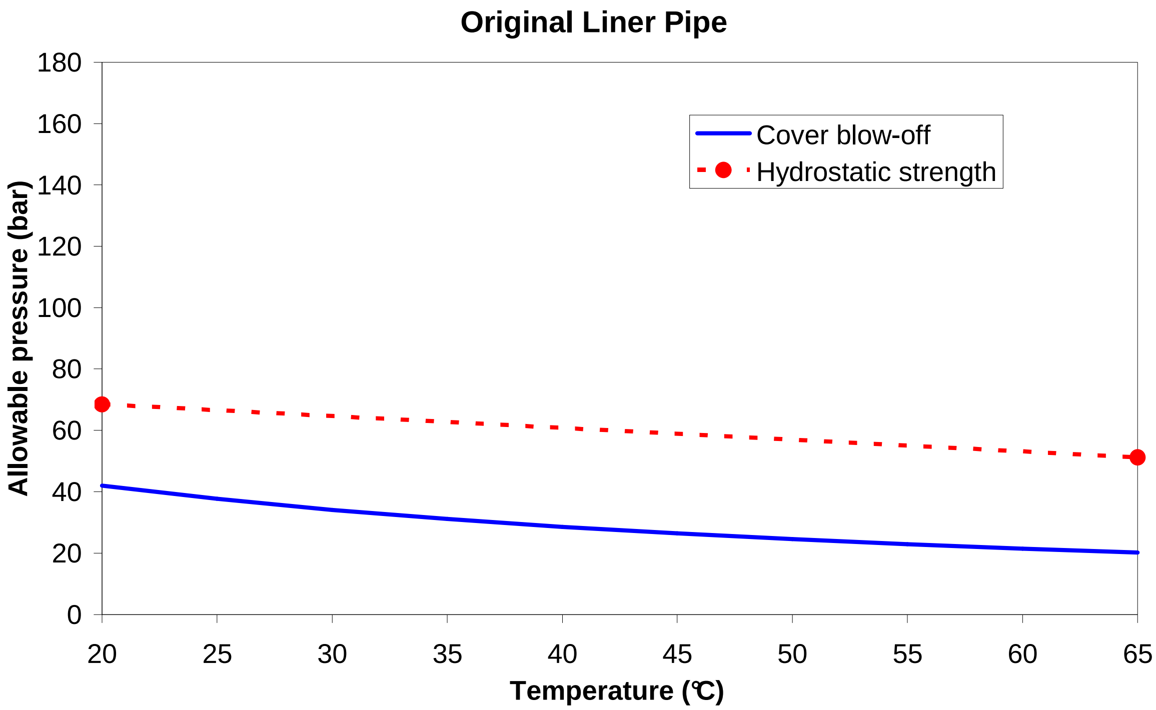


Figure 2. The allowable pressure inside a commercial RTP pipe with its original liner pipe as a function of temperature. The blue line is calculated with the described model. The two red dots are calculated using the 2-parameter model according to ISO 9080. The dotted red line is only there to guide the eye.

Comparing the allowable pressures for cover blow-off and the hydrostatic strength in Figure 2 results in a limiting factor of the cover blow-off over the entire temperature range. Although the hydrostatic strength of the RTP pipe is sufficient, the possible damage of the cover pipe restricts utilisation at high operating pressures.

To enable use of higher operating pressures, a new adjusted liner pipe is proposed. Around 10 % of a polyamide based permeation reducing additive has been added to the PE100 of this liner pipe. It therefore has a permeability coefficient of 7.0 ml·mm·m^{-2}·bara^{-1}·day^{-1} instead of 36.6 ml·mm·m^{-2}·bara^{-1}·day^{-1} (9). The strength is assumed identical, as the strength of the RTP pipe is determined by the unchanged reinforcement layer. In the near future, a 1000 hours spot-check according to ISO 9080 will be performed to verify this assumption. Furthermore, the heat conductivity and activation energy for permeation of the new liner pipe are assumed to be the same as for the original liner pipe. These last two parameters are not tested.

Again, the model is used to calculate which operating pressure in the RTP pipe results in a pressure in the annulus that is less than the determined threshold value. The threshold value remains the same because the cover pipe is not changed and thus blistering occurs at the same pressure in the reinforcement layer. The results are given in Figure 3.

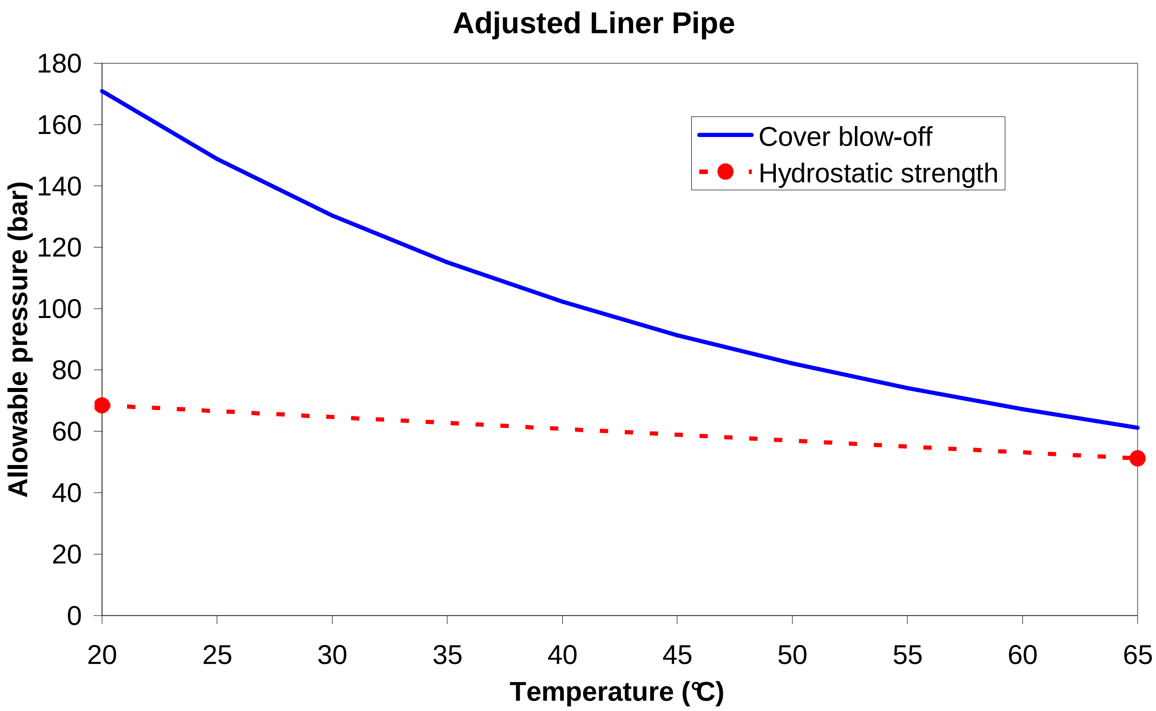


Figure 3. The allowable pressure inside a commercial RTP pipe with an adjusted liner pipe as a function of temperature. The blue line is calculated with the described model. The two red dots are calculated using the 2-parameter model according to ISO 9080. The dotted red line is only there to guide the eye.

The comparison between the allowable pressures for cover blow-off and the hydrostatic strength for the adjusted liner pipe in Figure 3 shows that this time the hydrostatic strength is the limiting factor over the entire temperature range. It is therefore possible to increase the operating pressure of the RTP pipe.

The described mathematical model can therefore be used to calculate the possible risk of cover blow-off at various temperatures and with different materials for RTP pipes.

FUTURE WORK

This theoretical model proved to be very effective in calculating the pressure in the reinforcement layer of RTP piping systems. However, additional experimental work should be performed to verify these calculations. The pressure in the reinforcement layer should be measured and compared to the calculated value. Because it can take several weeks to reach a steady state situation, this can only be done with RTP pipes where the cover blow-off is the limiting factor.

SYMBOL LIST

A_L	surface area of the liner pipe	r_L	outer radius of the liner pipe (mm)
D	diffusion coefficient ($m^2 \cdot s^{-1}$)	R	gas constant ($kJ \cdot mol^{-1} \cdot K^{-1}$)
e_C	wall thickness of the cover (mm)	R_{PL}	permeation resistance of the liner ($bara \cdot day\ ml^{-1}$)
e_L	wall thickness of the liner pipe (mm)	R_{PC}	permeation resistance of the cover ($bara \cdot day\ ml^{-1}$)
E_P	activation energy for permeation ($kJ \cdot mol^{-1}$)	S	solubility ($bara^{-1}$)
J_m	mass flux ($mol \cdot m^{-2} \cdot s^{-1}$)	T	absolute temperature (K)
J_T	heat flux ($J \cdot m^{-2} \cdot s^{-1}$)	T_i	temperature inside the pipe (°C)
L	length of the pipe (m)	T_o	temperature outside the pipe (°C)
p	partial pressure (bara)	T_R	temperature at the reinforcement layer (°C)
p_i	pressure inside the pipe (bara)	∂c	concentration difference ($mol \cdot m^{-3}$)
p_o	pressure outside the pipe (bara)	Δc	concentration difference ($ml \cdot ml^{-1}$)
p_R	pressure in the reinforcement layer (bara)	∂T	temperature difference (K)
P_C	permeation coefficient ($ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$)	∂x	distance (m)
P_{C0}	normalized permeation coefficient ($ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$)	λ	heat conductivity ($J\ s^{-1} \cdot m^{-1} \cdot K^{-1}$)
Q_V	volume of permeated gas ($m^3 \cdot s^{-1}$)	λ_L	heat conductivity of the liner ($J\ s^{-1} \cdot m^{-1} \cdot K^{-1}$)
Q_P	flow of permeated gas ($ml\ day^{-1}$)	λ_C	heat conductivity of the cover ($J\ s^{-1} \cdot m^{-1} \cdot K^{-1}$)
Q_T	heat flow through the pipe wall ($J\ s^{-1}$)		

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