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Simulation of buried pipe-in-pipe heat exchanger

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Abstract

The pipeline transportation of heavy crude oils is a difficult task, since the relatively high pour point of the liquid limits the heat loss of the transported medium. Since the viscosity increases nearly exponentially with temperature drop, the increased frictional pressure drop can quickly make the desired transportation task impossible. A pipe-in-pipe system can be utilized to heat the crude during transportation, keeping the frictional pressure drop at an acceptable level. In this paper a numerical simulation method is introduced that enables the design of buried pipe-in-pipe systems. The results are validated using the Aspen HYSYS process simulation software, the maximum error of the investigated example problem is 1.1%.

1 Introduction

The transportation of the produced crude from the wellsite to the gathering station can be carried out in several ways. It can be transported on road using trucks, on rail using trains, or using pipeline. The selection of the optimum transportation method is the result of a careful and detailed design process. The main parameters determining the transportation type are the properties of the liquid, the pressure and temperature condition of the wellhead, the required transportation distance and elevation profile, as well as the maximum flow rate. In this paper the pipeline transportation is investigated in depth. In this case usually a constant diameter pipeline connects the gathering station with the well. The pipeline is buried at 1 m depth, as a rule of thumb, different burying depths can be warranted based on the external conditions of the designed pipeline.

For heavy crudes to overcome the frictional losses, additional methods are required, since the heat transfer between the soil and the flowing medium changes the flow parameters. Flow characteristics of liquids are defined by the viscosity and temperature relationship. Since both the dynamic and kinematic viscosities vary with temperature, these properties must be measured at least two different temperatures to create an accurate model of the liquid for the investigation of its flow in a non-isothermal environment.

In this paper a pipe-in-pipe system is investigated in detail. Figure 1 shows the configuration of the outer and the inner pipe. In this system a heating medium is pumped in either the inner pipe, or in the annular space between the two pipes, whereas the second liquid is transferred in the other domain. In the past the heavy crude was transported in the annular space and heating water or steam was flowing in the inner pipe. This, however creates several problems from operation point of view. Firstly, the heavier components of the crude – waxes and/or asphaltanes – are deposited on the inner wall of the outer pipe as the temperature of the oil changes due to the heat exchange with the soil and. Secondly, the annular space cannot be cleaned using traditional pigging, the only available method is to increase the heating medium temperature to the point that all solidified materials liquefy. Therefore, the better approach is to pump the heavy crude inside the inner pipe, which can be easily maintained.

The flow directions have a profound effect on the heat transfer mechanism, changing the logarithmic mean temperature difference, which is directly proportional to the effectiveness of the heat exchanger. Co-current and countercurrent flow configurations change the temperature difference of the two media along the length.

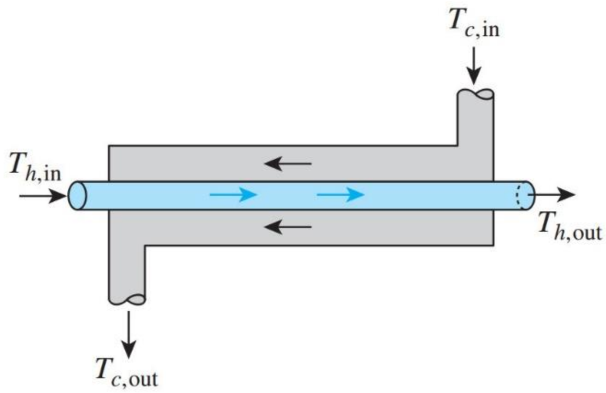

Figure 1 The configuration of the pipe-in-pipe system.

2 Example problem

To show the behavior of the pipe-in-pipe system, an example problem is solved. The input parameters required by the calculation procedure are listen in Table 1 and in Table 2.

1. *Table The parameters of the pipe-in-pipe system used in the example problem*

Inner pipe data			Outer pipe data		
OD_i	0.2191	m	OD_o	0.4570	m
dw_i	0.0127	m	dw_o	0.0127	m
ID_i	0.1937	m	ID_o	0.4443	m
L	10	km	k_s	45	W/mK

2. *Table The properties of liquids used in the example problem*

	Oil	Water	
T_{in}	60	90	°C
P_{in}	47	50	bar
m	7.75	19.44	kg/s
ρ	930	1000	kg/m³
c	2000	4190	J/kgK
k	0.13	0.598	W/mK
ν_{60}	140	0.474	mm²/s
ν_{70}	87	0.413	mm²/s

2.1 Calculation of only heavy crude oil flow

If the heavy crude is flowing inside the inner pipe, and no outer pipe with heating medium is used, the pressure traverse can be determined using the well-established Darcy-Weisbach and the Colebrook-White equations. The pipe must be segmented, because the effect of temperature on the flow parameters must be considered during the calculations.

Using more segments increases the accuracy of the calculation, but this has diminishing returns: increasing the number of segments above 100 does not improve the accuracy of the calculation significantly, therefore 100 m long segments were used in the determination process. Figure 2 shows the resulting pressure profile.

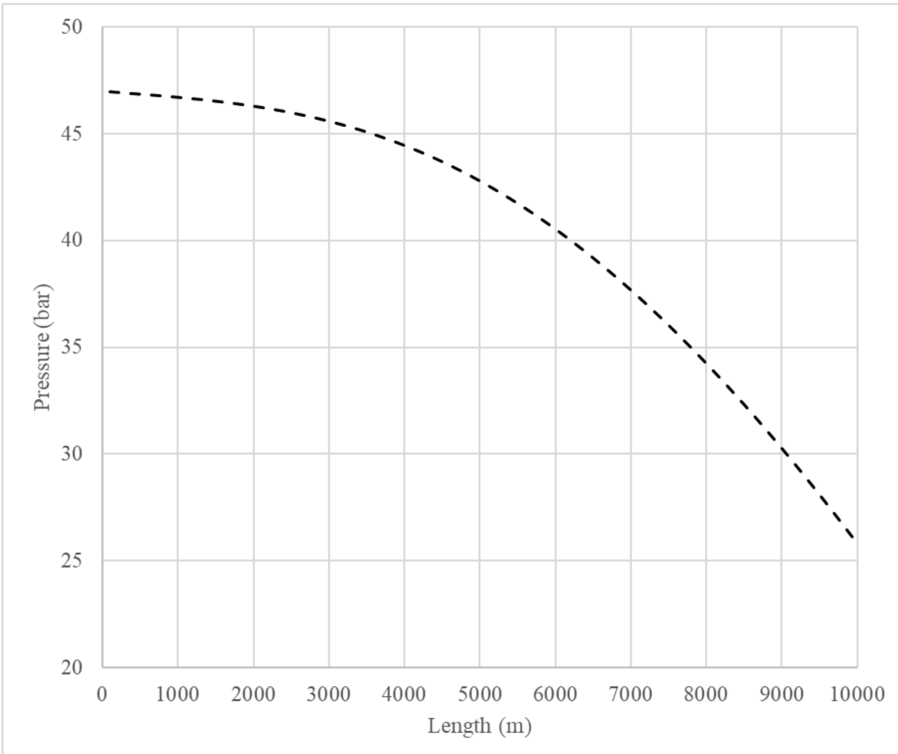

Figure 2 The pressure traverse curve of non-isothermal flow of heavy crude in pipe.

The temperature of the flowing oil was determined using Equation 1. [3]

$$T_2 = T_s + (T_1 - T_s) \cdot e^{-\frac{Kl}{mc}} \tag{1}$$

The overall heat transfer coefficient can be determined using the geometry of the pipe and the insulation, along with the properties of the flowing medium and the surrounding environment. Equation 2 describes the overall heat transfer coefficient. [2]

$$K = \frac{\pi}{\frac{1}{\lambda_1 ID_i} + \frac{1}{2k_{st}} \ln\left(\frac{OD_i}{ID_i}\right) + \frac{1}{2k_{in}} \ln\left(\frac{OD_{in}}{OD_i}\right) + \frac{1}{\lambda_2 OD_i}} \tag{1}$$

The pressure drop of the investigated pipeline is more than 21.2 bar, which results in an average pressure gradient of 0.002 bar/m. The internal and outer convection factors can be determined using the Grashof number, the Prandtl Number and Nusselt number. [2]

2.2 Calculation of the pipe-in-pipe system

To calculate the pressure traverse of the pipe-in-pie system, fist the temperature variation along the length of the two media must be determined, since their viscosities depend on dominantly the temperature, which greatly influences the frictional pressure drop. In the co-current flow configuration, the temperature profile of the water in the annular space can be calculated considering the components of the temperature change, as shown in Figure 3.

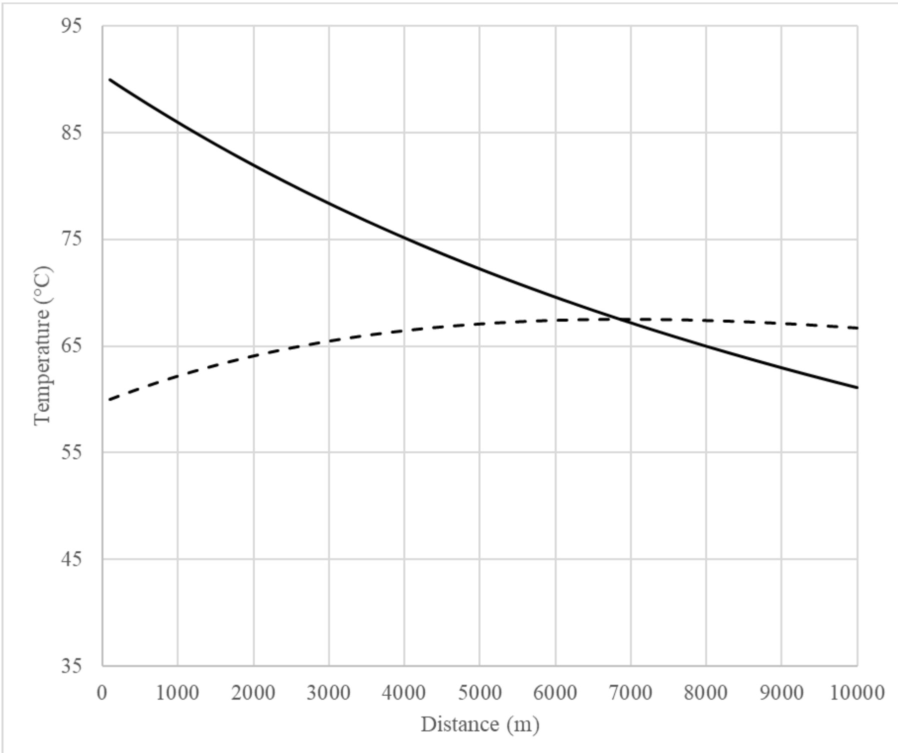

Figure 3 The temperature curves of the co-current pipe-in-pipe system.

The two components determining the temperature of the water are the heat transfer between the water and soil, and between the water and oil. In the co-current case the temperatures of the water and oil can be simultaneously calculated, since the initial temperatures at the inlet are known, and this temperature difference drives the heat transfer.

In the counter-current configuration the calculation is more complex, requires an additional iteration step, since the initial temperatures are known at different ends of the pipeline. Therefore, an initial temperature distribution must be assumed first for the water stream, since it is required for the calculation of temperature of the oil for each segment. In the investigated example case the best results were obtained when the water temperature drop in each segment was set initially to 0.7°C.

Thereafter the temperature values of the water were calculated from the soil temperature and the crude temperature. This recalculation was carried out, until the difference of the water temperature distribution before and after the calculation step was appropriately low. The results were finalized, when the sum of the squares of the temperature differences fell below 0.015. The final temperature distribution of the water and the crude is shown in Figure 4.

Comparing the results of the calculation shown in Figure 4 with the temperature profile of water calculated using the Aspen HYSYS software, the maximum difference is found to be 1.1%, as shown in Table 3.

The pressure distribution is heavily influenced by the size of the inner pipe using the same outer pipe dimensions. This is mainly a consequence of the inverse dependence of the frictional pressure drop on the square of the flowing velocity. Along with the pipe defined in the example problem two smaller nominal size pipes were investigated, the results of the calculation are shown in Figure 5. Using 0.1524 m inside diameter the frictional pressure drop increases nearly threefold, when the 0.1252 m inside diameter is used, a more than fivefold increase in frictional pressure drop can be observed. The inlet temperature of the water also has significant effect on the crude temperature distribution. Figure 6 shows five different scenarios, ranging from 90°C to 30°C.

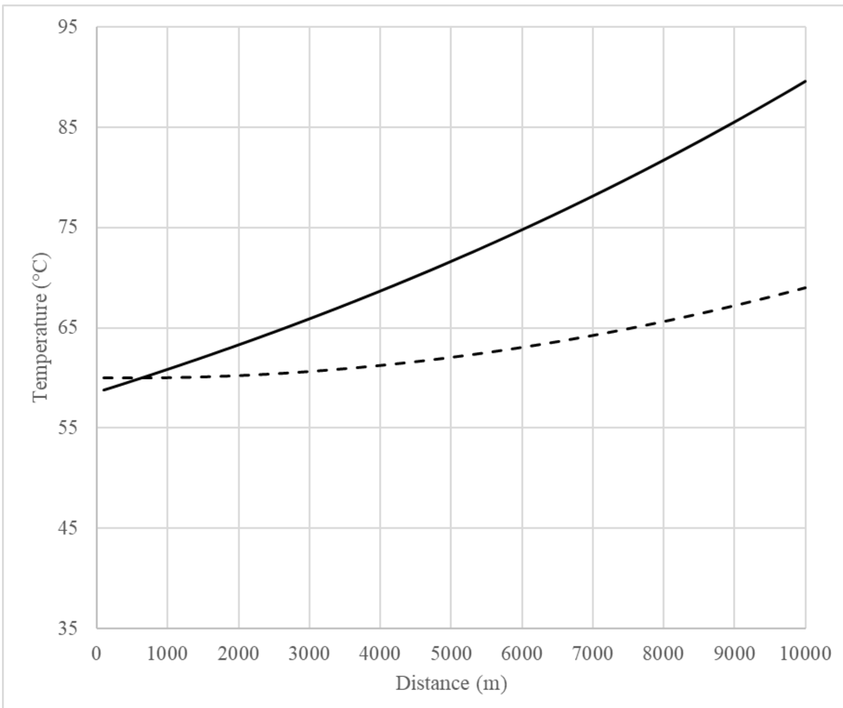

Figure 4 The temperature curves of the counter-current pipe-in-pipe system.

2. ***Table The comparison of the introduced method with the results of the Aspen HYSYS***

	Our work	HYSYS		Our work	HYSYS	
Distance (m)	Output temperature (°C)		Error (%)	Pressure (bar)		Error (%)
2000	60,21	60,27	0,098	46,38	46,42	0,09
4000	61,23	61,44	0,35	45,77	45,86	0,19
6000	63,02	63,47	0,71	45,21	45,34	0,29
8000	65,60	66,32	1,1	44,70	44,88	0,41
10000	68,96	69,73	1,11	44,25	44,48	0,52

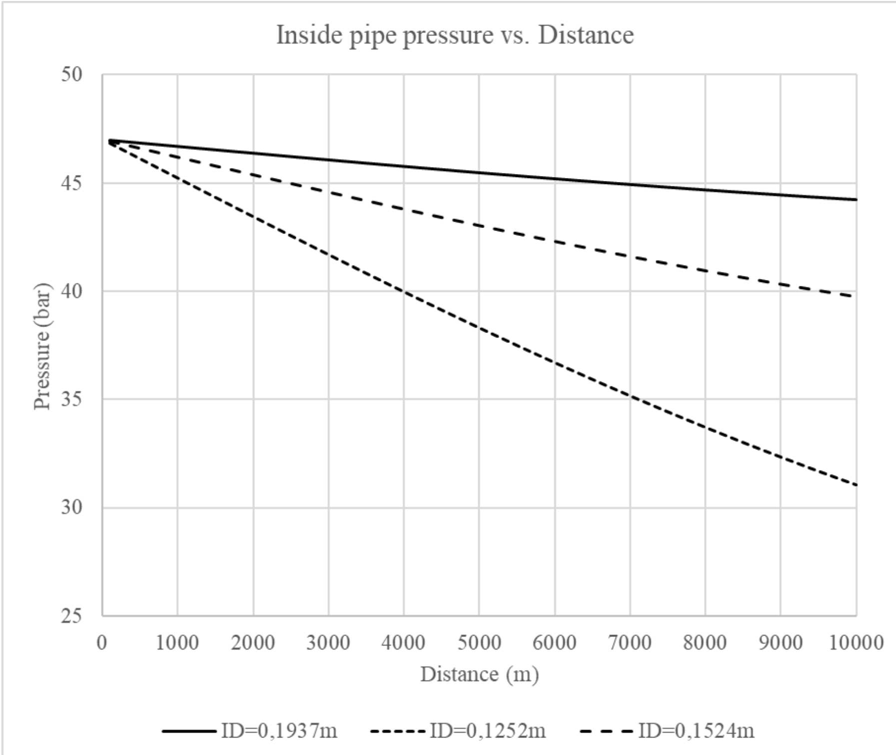

Figure 5 The effect of the inner pipe diameter on the pressure distribution.

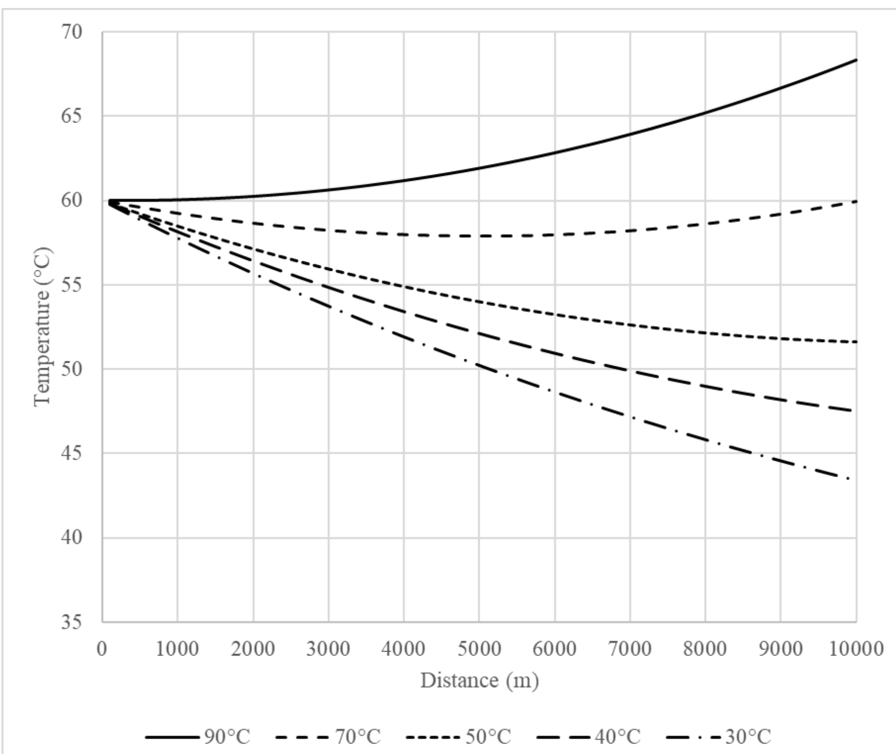

Figure 6 The dependence of the crude temperature profile on the water inlet temperature.

The result of this sensitivity analysis is also important in the design of the pipe-in-pipe system, since using too hot heating medium results in higher losses to the environment. As a guideline, the water temperature is optimal, when the crude temperature is approximately unchanged, or just slightly decreasing in the direction of the flow. Therefore, for the example pipe-in-pipe system the 70°C water inlet temperature is more favorable than the 90°C case.

3 Conclusions

One of the most practical transportation method of heavy crude oils is using a pipe-in-pipe system, which can be designed to meet the requirements set forth by the properties of the crude and the input physical parameters of the wellhead and the gathering station. In this paper a numerical method was introduced to model this complex system in both co-current and counter-current cases.

Sensitivity analyses were carried out to describe the behavior of the system depending on key design parameters, as the inner pipe dimensions and the water temperature. This calculation method is a novel approach, the pipe-in-pipe calculations were designed to describe the pipe-in-pipe exchangers, where the unit is not buried underground, therefore the heat losses to the environment were not previously included.

4 Acknowledgements

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5 Nomenclature

Symbol	Variable	Unit
OD_i	Outside diameter of the inner pipe	m
dw_i	Wall thickness of the inner pipe	m
ID_i	Inside diameter of the inner pipe	m
OD_o	Outside diameter of the outer pipe	m
dw_o	Wall thickness of the outer pipe	m
ID_o	Inside diameter of the outer pipe	m
L	Length of the pipe	m
k_s	Heat transfer coefficient of the pipe wall	W/mK
T_{in}	Inlet temperature of the heavy crude	°C
P_{in}	Inlet pressure of the heavy crude	bar

m	Mass flow of the crude	kg/s
ρ	Density of the crude	kg/m^3
c	Specific heat capacity of the crude	J/kgK
k	Heat transfer coefficient of the crude	W/mK
ν_{60}	Kinematic viscosity at 60°C	m^2/s
ν_{70}	Kinematic viscosity at 70°C	m^2/s
T_2	Temperature at the end of the segment	°C
T_1	Temperature at the start of the segment	°C
T_s	Soil temperature	°C
K	Overall heat transfer coefficient	W/mK
OD_{in}	Outside diameter of the insulation	m
λ_1	Internal convection factor	W/m^2K
λ_2	Outer convection factor	W/m^2K

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