

Theoretical and Numerical Analysis of Heat Transfer in Pipeline System

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Abstract

In this paper, analysis is conducted in both theoretical and numerical aspects on the heat transfer in a pipeline system via three steps: (1) Development of a theoretical model based on the heat transfer theory and existing work from literature; (2) Development of a corresponding MATLAB-based software for the evaluation of heat loss within the pipeline system; (3) Validation of the software via three-dimensional computational fluid dynamics (CFD) simulations using ANSYS FLUENT. It is concluded that the software can provide in-depth understanding of the heat transfer phenomena in pipelines and can be used for fast assessment of the heat loss in pipeline systems.

Keywords: Pipeline system; Software; Heat transfer.

Nomenclature

\dot{m}	Mass flow rate (kg/s)	λ	Thermal conductivity of liquid or gas (W/m·K)
q	Heat transfer rate (W)	t	Temperature (K)
h	Convection heat transfer coefficient (W/m ² ·K)	r	Radius (m)
H'	Specific enthalpy (kJ/kg)	x	Steam dryness
Re	Reynolds number	ρ	Density (kg/m ³)
Pr	Prandtl number	R_f	Fouling factor (W/m ² ·K)
Nu	Nusselt number	L	Length (m)
k	Thermal conductivity of solid (W/m·K)	η	Viscosity (kg/s·m)

Subscripts

in	Inlet	i	Inside
out	Outlet	o	Outside
eq	Equivalent	S	Sub-pipe

Introduction

Overhead pipelines were used extensively in both industrial and civic heat supply engineering (Zhang and Lu, 1998). Since pipeline systems are complex and the ambient environment is highly variable, how to quickly determine the heat loss of a pipeline system is a difficult problem for engineers and pipe network designers. Firstly, the pipeline structure and the mass flow distribution influence significantly on the convection heat transfer inside the pipeline (Yang, 2009). Secondly, the pipe material, the cladding material and the insulation have great effects on the heat conduction inside the pipe wall. Thirdly, the variable environmental parameters are challenges to the analysis of convection heat transfer outside the pipeline. Therefore, the heat transfer through the pipeline system is an interesting but challenging research topic.

In the present paper, based on the heat transfer theory, a theoretical model is established, and then the corresponding software is developed in MATLAB. In order to validate the software, several numerical case studies are carried out via a CFD code in ANSYS FLUENT. In addition, an example of application is presented to demonstrate the capability of the software. It is shown that the

software can assess the heat loss with acceptable accuracy and improve the computing efficiency significantly. It is thus a useful tool for engineers and pipe network designers

Theoretical model

As shown in Figure 1, the pipeline system in the present work consists of a main pipeline and several sub-pipelines, which is a common structure in industrial and civic heat supply engineering.

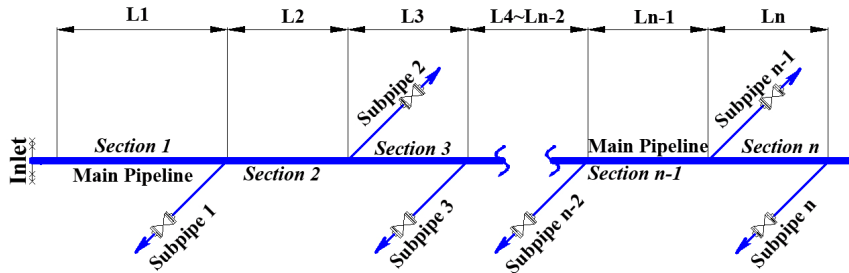


Figure 1. Structure of the pipeline system.

The mass flow rate in the main pipeline is a variable, which varies along the flow direction because of bypass flows. In order to solve this problem, the main pipeline is divided into several sections. Within each section the mass flow rate remains constant. Equation (1) shows the mass flow rate of each section, in which \dot{m}_1 represents the mass flow rate of Section 1, \dot{m}_2 the mass flow rate of Section 2, \dot{m}_n the mass flow rate of Section n , and so on.

$$\begin{aligned}
 \dot{m}_2 &= \dot{m}_1 - \dot{m}_{S1} \\
 \dot{m}_3 &= \dot{m}_2 - \dot{m}_{S2} \\
 &\dots\dots\dots \\
 \dot{m}_{n-1} &= \dot{m}_{n-2} - \dot{m}_{Sn-2} \\
 \dot{m}_n &= \dot{m}_{n-1} - \dot{m}_{Sn-1}
 \end{aligned} \tag{1}$$

Heat transfer process

Figure 2 shows a part of the pipeline, where the inner and outer surfaces are exposed to hot fluid and cold air respectively. The heat transfer process includes the convection inside the pipe, the conduction through the pipe, and the convection outside the pipe. The heat transfer process is presented in Figure 2 (a) and the distribution of temperature in Figure 2 (b).

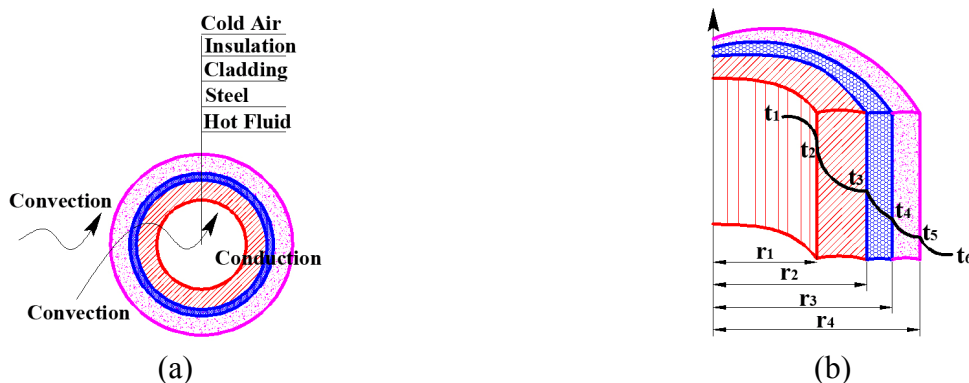


Figure 2. Heat transfer process and temperature distribution through pipe wall.

According to the thermal resistance theory, the heat transfer rate through the pipe wall is presented as (Bergman, Incropera *et al.*, 2011)

$$q = \frac{t_1 - t_6}{\frac{1}{2\pi r_1 L h_i} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L} + \frac{1}{2\pi r_4 L h_o} + R_f} \quad (2)$$

where t stands for the temperature, r the radius, k the thermal conductivity, h the convection heat transfer coefficient, and L the length respectively. In practical analysis, although the outside air temperature t_6 is usually considered as a constant, the inside fluid temperature t_1 is a variable since it varies along the flow direction. By analysis and calculation, it is concluded that the temperature difference ($t_1 - t_6$) may be assumed to be the log mean temperature difference. As a result, Equation (2) is modified to

$$q = \frac{\frac{t_{in} - t_{out}}{\ln\left(\frac{t_{in} - t_{air}}{t_{out} - t_{air}}\right)}}{\frac{1}{2\pi r_1 L h_i} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L} + \frac{1}{2\pi r_4 L h_o} + R_f} \quad (3)$$

In Equation (3), there are three unknowns, i.e. the inside heat transfer coefficient h_i , the outside heat transfer coefficient h_o , and the outlet temperature t_{out} , which will be figured out by analyses of convection heat transfer inside and outside the pipeline.

Heat transfer inside the pipeline

In industrial and civic heat supply engineering, the most common fluid inside includes hot water and steam. Although the heat transfers of these two fluids are all forced convection, the phase change of steam gives more challenge to the analysis in steam pipeline systems. In addition, the heat transfer inside the pipeline is an internal convection, such that another important characteristic is that the fluid is confined by the surface wall of the pipeline. As a result, the heat transfer phenomena inside pipeline are thus closely associated with the characteristic of the hot fluid and the dimension of the pipeline.

For hot water, the Dittus-Boelter equation as a classical expression for computing the Nusselt number of fully developed turbulent flow in a circular tube is given as (Tao, 2001),

$$Nu_{water} = 0.023 Re^{0.8} Pr^n \quad (4)$$

where $n = 0.4$ for heating and $n = 0.3$ for cooling.

By Equation (4) and the definition of the Nusselt number (Tao, 2001), the inside convection heat transfer coefficient for water $h_{i-water}$ is thus expressed as

$$h_{i-water} = 0.023 \frac{\lambda}{d_{in}} Re^{0.8} Pr^{0.3} \quad (5)$$

while Re stands for the Reynolds number, and Pr the Prandtl number respectively.

For steam, the condensation of steam has to be considered in the heat transfer process. Condensation is a phase change process from vapor to liquid. It occurs when the steam strikes the pipe wall whose surface is at a temperature below the steam saturation temperature and the steam releases latent heat and converts to a liquid phase immediately (Tandon, Varma *et al.*, 1995). Several empirical and semi-empirical correlations were suggested and one of the most widely used correlations is the Ackers Equation as follows (Yang and Webb, 1996).

$$Nu_{steam} = C Re_{eq}^n Pr_{liquid}^{\frac{1}{3}} \quad (6)$$

where $C = 0.0265$, $n = 0.8$ for $Re_{eq} > 5 \times 10^4$, and $C = 5.03$, $n = 1/3$ for $Re_{eq} < 5 \times 10^4$.

In Equation (6), the equivalent Reynolds number Re_{eq} is given by (Yang and Webb, 1996)

$$Re_{eq} = \frac{\dot{m}_{eq} d_{in}}{\eta_{liquid}} \quad (7)$$

where \dot{m}_{eq} stands for the equivalent mass flow rate, d_{in} the inside diameter, η_{liquid} the viscosity of the liquid. Equation (8) gives the expression of \dot{m}_{eq} , in which x means the steam dryness and ρ the density.

$$\dot{m}_{eq} = \dot{m} \left[(1-x) + x \left(\frac{\rho_{liquid}}{\rho_{vapor}} \right)^{\frac{1}{2}} \right] \quad (8)$$

The inside convection heat transfer coefficient for steam $h_{i-steam}$ is thus obtained as

$$h_{i-steam} = C \frac{\lambda_{liquid}}{d_{in}} Re_{eq}^n Pr_{liquid}^{\frac{1}{3}} \quad (9)$$

Heat transfer outside the pipeline

The heat transfer from pipe wall to outside air is an external heat convection between solid boundary and moving fluid. In general, pipeline systems are exposed to the surrounding, such that the meteorological conditions have a great influence on the heat loss of the pipeline systems. A well-known empirical correlation contributed by Hilpert is presented as (Rathore and Kapuno, 2011)

$$Nu = C Re^n Pr^{\frac{1}{3}} \quad (10)$$

while Re stands for the Reynolds number, and Pr the Prandtl number respectively. C and n are constants and tabulated in Table 1 at various Reynolds numbers. This empirical correlation is widely used for $Pr \geq 0.7$.

Table 1. The values of C and n (Rathore and Kapuno, 2011)

Re	C	n
0.4~4	0.989	0.330
4~40	0.911	0.385
40~4000	0.683	0.466
4000~40000	0.193	0.618
40000~400000	0.0266	0.805

According to Equation (10) and the definition of the Nusselt number (Tao, 2001), the outside convection heat transfer coefficient h_o is thus presented as

$$h_o = C \frac{\lambda}{d} Re^n Pr^{\frac{1}{3}} \quad (11)$$

Energy equation

Considering the pipeline and the inside fluid as a whole system, when using the first law of thermodynamics, the energy equation for water pipelines is obtained as

$$q_{water} = \dot{m} (H'_{in} - H'_{out}) \quad (12)$$

For steam pipelines, the condensation has to be considered and the energy equation becomes

$$q_{steam} = \dot{m} x (H'_{steam-in} - H'_{steam-out}) + \dot{m} (1-x) (H'_{water-in} - H'_{water-out}) \quad (13)$$

while q stands for the energy, H' the specific enthalpy, m the mass flow rate, and x the steam dryness.

Equations (1) ~ (13) represent the entire heat transfer process through the pipeline such that the theoretical model for assessing heat loss of the present pipeline system is established.

Development of the software

Based on the theoretical model of the present pipeline system, a software is written and debugged using MATLAB R2012b, under Windows operating system. MATLAB is a high-level technical computing language and interactive platform for algorithm development, data visualization, data analysis, and numeric computation (Özgü Arısoy and Dikmen, 2011).

All the equations in the theoretical model as mentioned above are formulated first with MATLAB source code, in which an iterative computational technique is used to solve the problem. After that, Graphical User Interface (GUI) is adopted to create the user-friendly interface. Furthermore, the testing and debugging of the module are conducted backstage as MATLAB is internally packaged

with an editing and debugging functionality (Sen and Shaykhian, 2009). Finally, the software is published as an executable file that can be used in normal computers, even without MATLAB installed.

Figure 3 shows the main user interface of the software, which includes Parameter Input, Control Function, Output Display, and Database. Parameter Input is used to input basic parameters, including hot fluid parameters, pipeline structures, environmental parameters, and so on. Control Function is used for start or stop of the calculation, modification of the input data, and quit from the software. Output Display is designed for exporting the computational results. The clear and concise user interface enable user to operate the software easily and thus significantly improve the efficiency.

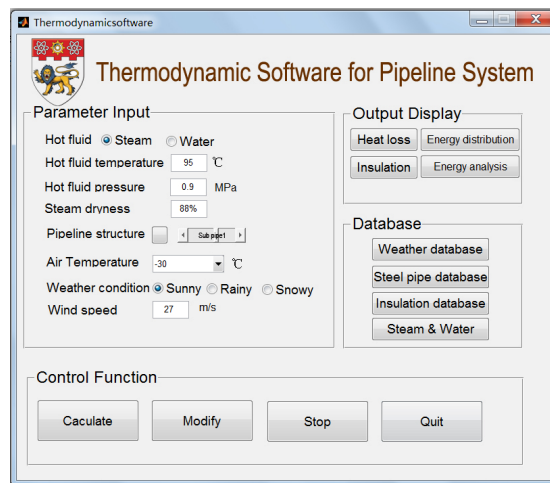


Figure 3. Main user interface of the software.

Validation of the software

As well known, ANSYS FLUENT as a CFD tool has a long history for simulation of the pipeline heat transfer process and for optimization of the pipeline structure (Li, Zhao *et al.*, 2012). Therefore, it is adopted to simulate the fluid flow and temperature field in the present pipeline system for validation of the software developed. In the present work, a model containing a main pipeline and two sub-pipelines is created and analyzed numerically. The fluid is hot water with the inlet temperature 85 °C and the inlet pressure 0.5 MPa. The ambient air temperature is set to be 0 °C, and the outside convection heat transfer coefficient h_o is set as 10, 20, 30, 40, 50 W/m²·K, respectively.

In the simulation, SOLIDWORKS is used to create the 3-D geometry model of this pipeline system. The grid selected has achieved its convergence through a sensitivity study. The Pressured-Based solver in steady heat transfer approach is used for simulation. The Standard $k-\varepsilon$ model is adopted to model the turbulence in the pipe flow. Through simulation, the temperature distribution of the pipeline is obtained, and the heat loss of the pipeline system is then calculated according to the enthalpy difference of the fluid at the inlet and the outlet, by (Moran, Shapiro *et al.*, 2010).

$$q = \dot{m}(H'_{in} - H'_{out}) \quad (17)$$

where q stands for the heat loss, H' the specific enthalpy, and m the mass flow rate.

The results from ANSYS FLUENT and the software are compared. As shown in Figure 4, the difference is generally less than 15%, and less than 10% when the outside heat transfer coefficient ranges from 10 to 30 W/m²·K, which are usual values in practical applications. It is thus concluded that the software can achieve results with acceptable accuracy and can be used in practical applications.

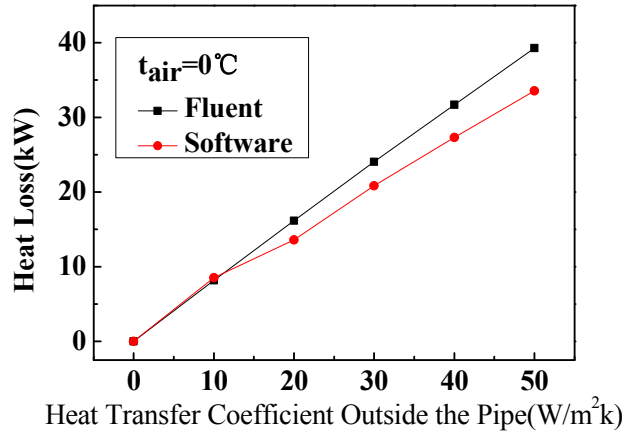


Figure 4. Comparison of the results between FLUENT and the software.

Case study

In this section, a steam pipeline in a cargo heating system is employed to demonstrate the function and capability of the software. In the cargo heating system, the pipeline plays a role of conveying steam from boiler to cargo tanks continuously. The fluid in this case study is saturated steam with the inlet temperature of 181 °C and the pressure of 0.9 MPa. The structure of the present pipeline system includes a main pipeline and 12 sub-pipelines. By inputting the basic information into the software, the heat loss of the pipeline system with various outside parameters is obtained.

Figure 5 shows the effects of the wind speed on the heat loss of the pipeline system subject to different air temperatures. The heat loss of the pipeline system increases sharply with the increase of wind speed. The reason is that the wind speed enhances the convection heat transfer outside the pipe and thus more heat transfers to the cold environment (Rohsenow, Hartnett *et al.*, 1998).

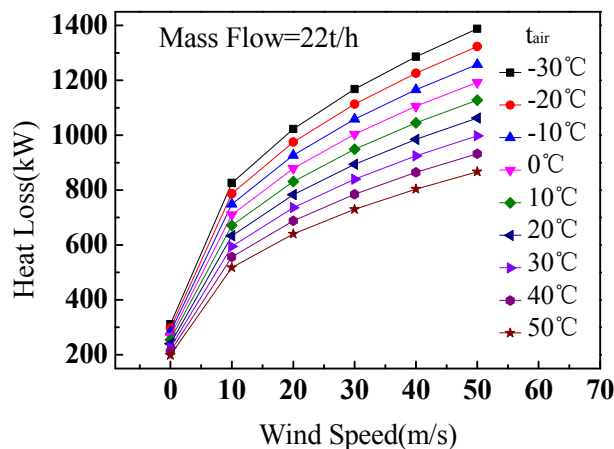


Figure 5. Effects of wind speed on the heat loss of the pipeline system.

As shown in Figure 6, the heat loss of the pipeline system decreases sharply with the increase of insulation thickness, even with just several millimeters. This is because the additional insulation increases the conduction resistance significantly, resulting in less heat transfers to the ambient air (Lin, Guo *et al.*, 2005). Such that it is strongly recommended that the present pipeline system needs to be insulated for about 20 mm for energy saving. It is also observed that there is only a marginal effect when the insulation thickness is more than 30 mm. This study indicates that this software can be used for the optimization of the pipeline insulation.

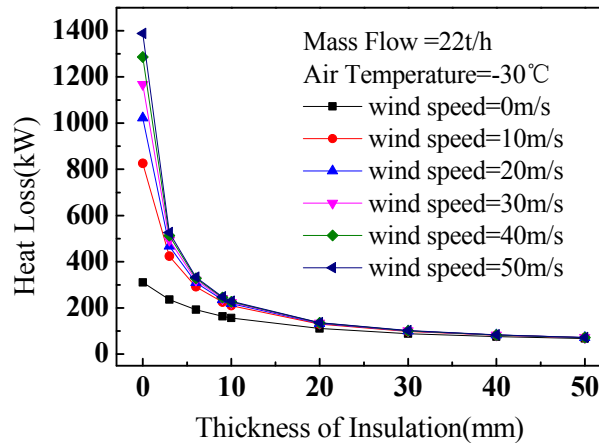


Figure 6. Effects of insulation on the heat loss of the pipeline system.

Conclusions

Based on the heat transfer theory, a theoretical model is established, and its corresponding MATLAB-based software is developed for assessment of the heat loss of pipeline systems. The software can obtain results with acceptable accuracy as the comparison between the software and ANSYS FLUENT shows a reasonable agreement. The software can save analysis time significantly when compared with the ANSYS FLUENT based models. It also has a user-friendly interface, which ensures the easy use for engineers and other customers without thermodynamics background. In summary, the software not only provides an easy way for fast assessment of the heat loss, but also offers a useful tool for the optimal design and energy saving analysis of pipeline systems.

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