Experimental Investigation on Thermal Properties of a Steel-jacketed Steam Heating Pipeline with Vacuum Insulation

Wei Na* Pinghua Zou
Doctoral Candidate Professor
Department of Building Thermal Engineering, Harbin Institute of Technology
Harbin P. R. China, 150090
hitnawei@yahoo.com.cn

Abstract: The steel-jacketed steam heating pipeline employs vacuum insulation to improve the insulating effect and reduce the corrosion, and hence increases the heat transfer efficiency of the heating network and building energy efficiency. It is important in improving the thermal insulation to investigate the impact of factors that insulate the effects and thermal properties of the pipeline. The thermal insulation of this pipeline comprises the vacuum layer and the insulating material layer. Experiments were performed to measure the combined heat transfer and equivalent thermal conductivities of the insulating material in the vacuum and rarefied air employed in the pipeline's insulation. The thermal properties of this type of insulation at vacuum pressures of 0.5~1013mbar, employing thermal media temperatures of 343~573K and with different thicknesses of vacuum layer, are discussed for this pipeline, for which diameters of inner steel pipe/steel jacket are DN50/DN250, DN100/DN300, DN200/DN500 and DN500/DN850, respectively. The results show that reduction in vacuum pressure reduces the heat loss in the pipeline. The equivalent thermal conductivity of the insulating material layer is distinctively lower than the vacuum layer, but decreasing the vacuum pressure improves the insulating effect of vacuum layer substantially more than insulating the material layer. As the vacuum pressure decreases from 1013mbar (atmospheric pressure) to 10mbar at the thermal media temperature of 523K e.g., the reduction of equivalent thermal conductivities of vacuum layer is approximately three times greater than that of insulating material layer. The equivalent thermal conductivities of the vacuum layer are lower and decease faster as the vacuum pressure is lower than 100mbar, but the equivalent thermal conductivities of insulating material layer are lower and decease faster as the vacuum pressure is lower than 50mbar. The pressure in vacuum insulation should be controlled lower than 20mbar to achieve desirable insulating effects. Every 10mm addition of thickness of insulating material layer (every 10mm reduction of thickness of vacuum layer) decreases the heat loss of approximately 6.8 percent at the vacuum pressure of 0.5mbar.

Key words: thermal properties; vacuum insulation; heating pipeline; equivalent thermal conductivity; steel jacket

1. INTRODUCTION

The heating pipeline employs the vacuum insulation to improve the insulating effect and reduce the corrosion, and hence, increase the heat transfer efficiency and reliability of heating network, further, the building energy efficiency. Vacuum insulated pipe(VIP) has been manufactured in the early 1950's by Ohio State University Dr. Herrick L. Johnson as a low heat leak transfer system for many cryogenic fluids at -269°C [1]~[6]. Since then, it has been used extensively for most other cryogenic fluids including liquid nitrogen, liquid oxygen, liquid hydrogen, liquid helium, and liquid methane (LNG) as well as for Industrial gas suppliers, national laboratories, aerospace companies, NASA etc.

The pressure of vacuum insulation in the vacuum insulated steam directly buried heating pipeline belongs to low vacuum (above 0.5mbar), and it differs from the vacuum insulation employed in cryogenics and spaceflight field in its vacuum

* Corresponding author. Tel.:+86 451 82291545; Fax.: +86 451 86282123
E-mail address: hitnawei@yahoo.com.cn

pressure. The vacuum pressure in cryogenics and spaceflight field is high or medium vacuum (below 0.01mbar). In 1979, the vacuum insulation came into use in directly buried heating pipeline in Germany[7]. In 1980s, Deimling and Axel(in 1983), Mosler, Jürgen and Strohrmann,M(in 1987), Rath and Dieter(in 1989) launched experiments and simulations on employing vacuum insulation in directly buried heating pipeline and proving its feasibility[8~11], respectively. However, to the best of the author's knowledge, no data have been reported in the open literature on the thermal properties for vacuum insulation in the heating pipeline with steel jacket tested in vacuum as a function of pressure and temperature, especially as the vacuum insulation is in low vacuum. In China, there has no been found in open literatures on it. Even now, the reasonable vacuum pressure, the thermal properties of insulating material layer and vacuum layer in vacuum insulation, and the thermal performance of the pipeline have not been discussed yet.

The objective of the present work is to measure experimentally the heat transfer of steel jacketed vacuum insulated heating pipelines and equivalent thermal conductivities of vacuum layer and insulating material layer for inner steel pipeline's temperatures between 343 and 573K with pressures from 0.5 to 1013 mbar, respectively. In addition, Effect of thermal characters on heat properties of vacuum layer and insulating material layer, i.e. vacuum pressure, temperature of inner steel pipeline etc, were analyzed. Equivalent thermal conductivities of vacuum layer and insulating material layer were compared. Finally, the way to improve this insulation of this type of heating pipeline was presented.

2. VACUUM INSULATED DIRECTLY BURIED HEATING PIPELINE

The schematic of the vacuum insulated steam heating pipeline is shown in Fig. 1. Vacuum insulated pipeline systems actually are a pipe within a pipe. It is comprised of inner pipeline and insulating material layer, vacuum layer, steel jacket pipeline and anticorrosive layer. The typical material of the inner pipeline and steel jacket pipeline is ASTM A312, 304/304L stainless steel or carbon steel, and the conventional material of insulating material layer is the micro glass wool.

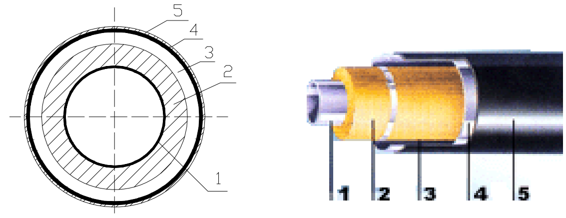

Fig. 1 Schematic of the vacuum insulated heating pipeline with steel jacket

Tab. 1 Components of vacuum insulated heating pipeline with steel jacket

Number	Components
1	Inner steel pipeline
2	Insulating material layer
3	Vacuum layer
4	Steel jacket pipeline
5	Anticorrosive layer

3. EXPERIMENTAL SETUPS

Thermal analysis was based on a dedicated steady-state experiment on the heat transmission of the pipeline. Experiments were carried out in a laboratory built on the basis of Chinese National Standards (Code: GB10296-1988, GB/T17357-1998 and CJ/T140-2001) [12~14] and international standards (Code: ASTM C1041-85(2001) and ISO 8497(1997)).

The sketch of experiment setup and test chamber is shown in Fig. 2 and Fig. 3, respectively. The components of experimental setup are listed in Tab. 2, and the equipments in test chamber are listed in Tab. 3. The arrows in Fig. 2 indicate the direction of thermal transfer oil flow. In our experiment[15], the sample is 3 meters long, and the diameters of the inner steel pipeline and steel jacket pipeline of the selected sample are 57~580mm and 273~870mm, respectively. Thicknesses of the insulating material layer are 50~140mm, and the apparent density of the insulating material is 35kg/m^3. Heat transfer oil in inner steel pipeline is controlled in five temperatures (130, 180, 200, 250 or 300℃) and the air in the test chamber is controlled in 25℃ (control precision:

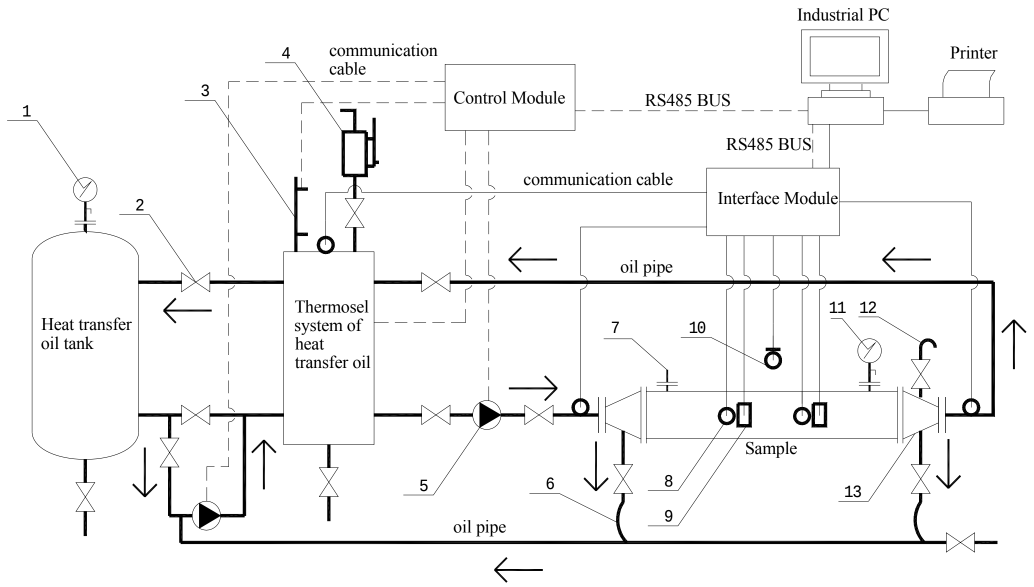

Fig. 2 Sketch of the experimental setup for testing thermal properties of vacuum insulated heating pipeline

±0.5℃) and 40%RH(control precision: ±2%RH), by an auto-control device. Vacuum insulation is controlled in five pressures (0.5, 10, 20, 50, 100 and 1013mbar) (control precision: ± 0.05%F.S). Thermocouples (precision: ±0.1℃) were used to test the temperature of the interface or surface on each layer of this pipeline (testing points are the top, bottom and the point made the angle of 2π/3 with the vertical direction), and heat flux gauge (precision: ± 0.5 %) and electrical resistance hygrometer(precision: ±0.1%RH) was used to test heat flux of surface and humidity of testing environment in the test chamber, accordingly.

Tab. 2 Components of experimental setup for testing thermal properties of vacuum insulated heating pipeline with steel jacket

Number	Components
1	Pressure gauge
2	Valve
3	Level gauge for transfer oil
4	Air bleeder
5	Transfer oil pump
6	Flexible mental pipe
7	Vent for vacuum pump
8	thermocouple
9	Heat flux gauge
10	hygrometer and thermocouple
11	Vacuum gauge
12	Air bleeder for the sample
13	Sample fitting

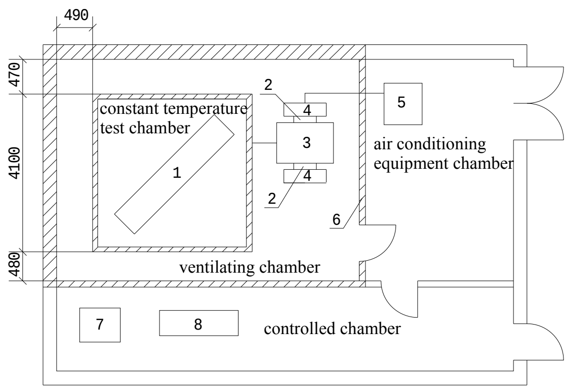

Fig. 3 Sketch of test chamber for testing thermal properties of vacuum insulated heating pipeline

Tab. 3 Equipments in the test chamber for testing thermal properties of vacuum insulated heating pipeline

Number	Equipments
1	Sample
2	Air heater
3	ventilator
4	Air cooler
5	refrigerator
6	Envelope for testing chamber
7	Power supply and switches
8	Control console for experimental equipments and setup

4. EXPERIMENTAL RESULTS AND ANALYSIS

Fig. 4 shows the heat transfer vs. pressure in insulation with inner steel pipeline at 200, 250 or 300□. The heat transfer decreases with the drop of pressure, e.g. the condition that inner steel pipeline's temperature is at 200□, the heat transfer drops by 4.0%, as the pressure decreases from 1013mbar to 50mbar. However, the heat transfer is lower and drops faster with the pressure, as the pressure is lower than 50mbar. As the pressure decreases from 1013mbar to 20mbar, the heat transfer drops by 18.4%, and by 27.0% as the pressure decrease from 1013mbar to 10mbar, respectively. It is obvious that the heat transfer drops sharply, as the pressure is under 20mbar, in contrast to that of pressure of 1013mbar. Thus, the pressure in insulation should be controlled lower than 20mbar to achieve desirable insulating effect.

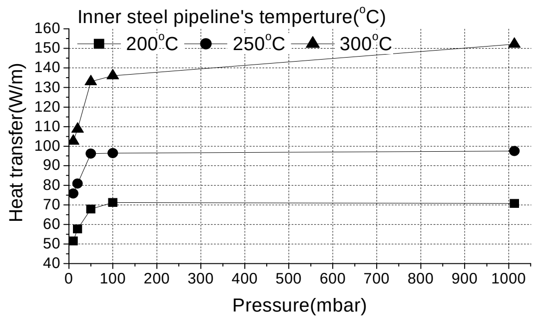

Fig. 4 Measured heat transfer of pipeline variation as a function of pressure and measured inner steel pipeline's temperature

E.g. the condition that the pressure decreases from 1013mbar to 20mbar, as the inner steel pipeline is at 300□, the heat transfer drops by 28.5%, and it is higher than that of which the inner steel pipeline is at 200□ and 250□, the heat transfer drops by 18.4% and 17.0%, respectively. Therefore, it is obviously that the higher temperature of the inner steel pipeline results in the more heat transfer and the faster the heat transfer increases with the pressure.

Fig. 5 shows the equivalent thermal conductivity of insulating material layer vs. mean temperature of insulating material layer at pressure of 10mbar~1013mbar. Furthermore, the curve of thermal conductivity variation as a function of mean temperature of insulating material, which is calculated by conventional method, is also shown in Fig. 5.

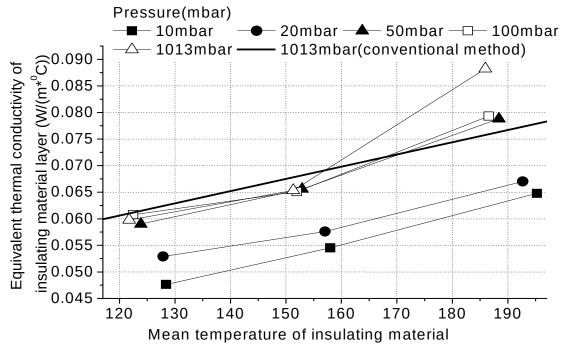

Fig. 5 Measured equivalent thermal conductivity of insulating material layer vs. mean temperature of insulating material layer at 10~1013mbar

It is obvious that the equivalent thermal conductivities of insulating material are strong functions of both temperature and pressure. The curves of measured equivalent thermal conductivities are distinctively different to that of thermal conductivity calculated by conventional method, which is only the function of temperature. As the pressure decrease from 1013mbar to 50mbar, 20mbar and 10mbar, the measured equivalent thermal conductivities drop by 3.9%, by 15.8 and by 21.2%, respectively. Therefore, the insulating effect is improved by decreasing the pressure. Furthermore, the insulating effect rises distinctively, as the pressure is below 20mbar.

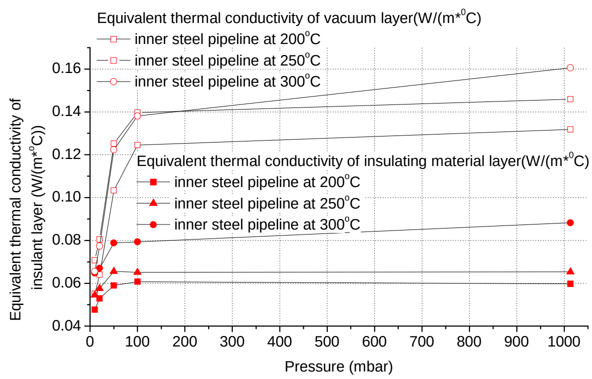

Fig. 6 Comparison of equivalent thermal conductivity of vacuum layer and insulating material layer

Fig. 6 shows the comparison of equivalent thermal conductivity of vacuum layer and insulating material layer, as the inner steel pipeline's temperature is at 200~300□ and the pressure is from 10mbar to 1013mbar, respectively.

Firstly, At all the temperature of the inner steel pipeline (i.e. at 200~300℃ according to our experiment), the equivalent thermal conductivities of vacuum layer and insulating material layer all decease with the pressure. The equivalent thermal conductivity of vacuum layer is obviously higher than that of insulating material layer, however, the gap of them drops sharply with the pressure. E.g. the inner steel pipeline is at 250℃, the equivalent thermal conductivity of vacuum layer at 1013mbar is 123.2% higher than that of insulating material layer. At 10mbar, the equivalent thermal conductivity of vacuum layer, however, is only 29.7% higher than that of insulating material layer. Secondly, As the pressure decreases from 1013mbar to 10mbar, the equivalent thermal conductivities of vacuum layer and insulating material layer drops by 51.5% and by only 16.6%, respectively. It shows that the equivalent thermal conductivity of vacuum layer is higher and drops faster with the pressure than that of insulating material layer. Thirdly, Fig. 6 also shows, as the pressure is below 100mbar, the equivalent thermal conductivity of vacuum layer start to drop sharply with pressure, however, that of insulating material layer start to drop sharply with pressure, as the pressure is below 50mbar. Thus, at the pressure of 10~1013mbar, measured the equivalent thermal conductivity of the insulating material layer is lower than that of the vacuum layer distinctively, but decrease of vacuum pressure improves much more insulating effect of vacuum layer than that of insulating material layer.

Tab. 4 shows heat transfer vs. thicknesses of vacuum layer and insulating material layer for four different sizes of typical samples, of which inner steel pipeline/steel jacket pipeline is DN50/DN250, DN100/DN300, DN200/DN500 and DN500/DN850 in diameter, respectively, at the inner steel pipeline's temperatures of 130~300℃, at 0.5mbar. And the material in the insulating material layer is the micro glass wool. The measured heat transfer of all the samples decreases with the drop of the thicknesses of the insulating material at the inner steel pipeline's temperatures of 130~300℃. As the insulating material of insulating material layer is in the increment of 10mm in each sample (i.e. the annual space of vacuum layer is in the reduction of 10mm in each sample), the heat transfer drops by ~6.8%. For vacuum insulated heating pipeline with steel jacket product, the absolute pressure of vacuum insulation employed is usually above 0.5mbar, and the equivalent thermal conductivity of the insulating material layer is lower than that of vacuum layer at 0.5~1013mbar, however, one of the most important function of vacuum layer is to decrease the equivalent thermal conductivity of insulating material and then to improve the insulating effect of insulating material layer greatly. Thus, on the premise of meeting required deflating space, which is necessary

Tab. 4 Heat transfer vs. thicknesses of vacuum layer and insulating material layer at 0.5mbar

Diameter(DN)		Radial thickness(mm)		Heat transfer(W/m)			
inner steel pipeline	steel jacket pipeline	vacuum layer	insulating material layer	inner steel pipeline at 130℃	inner steel pipeline at 180℃	inner steel pipeline at 250℃	inner steel pipeline at 300℃
50	250	58	50	15.6	23.3	35.6	45.6
		48	60	14.3	21.4	32.6	41.6
		38	70	13.3	19.9	30.3	38.7
100	300	58.5	50	23.6	35.3	54.0	69.2
		48.5	60	21.3	31.9	48.6	62.2
		38.5	70	19.6	29.3	44.6	57.0
200	500	65	90	25.9	38.7	59.0	75.4
		55	100	24.3	36.4	55.4	70.7
		45	110	23.1	34.4	52.4	66.9
500	850	50.5	120	43.2	64.3	97.4	124.1
		40.5	130	41.2	61.3	92.8	118.0
		30.5	140	39.5	58.7	88.7	112.8

to deflating and maintain the vacuum pressure for the insulation, it's always helpful for improving the insulating effect to add the thickness of insulting material layer and reduce the thickness of vacuum layer, accordingly.

5. CONCLUSIONS

The paper presents new experimental measurements of the thermal conductivity of vacuum insulation with pressures from 0.5 to 1013 mbar for temperatures of inner steel pipeline at 130~300℃. Measured data show heat transfer of this pipeline is a strongly degressive function of vacuum pressure of insulation, especially when this insulation is below 50mbar. Equivalent thermal conductivity of insulating material layer is lower and drops sharper with vacuum pressure than that of vacuum layer distinctively. As the vacuum pressure decreases from 1013mbar to 10mbar (Inner steel pipeline temperature is at 250℃ e.g.), the reduction of equivalent thermal conductivities of vacuum layer is about 3 times greater than that of insulating material layer. Vacuum pressure of this pipeline should be controlled below 20mbar to achieve desirable insulating effect. Every 10mm addition of thickness of insulating material layer (every 10mm reduction of thickness of vacuum layer) decreases the heat loss of approximately 6.8% at the vacuum pressure of 0.5mbar. Therefore, the vacuum insulated heating pipeline is a promising alternative to improve the thermal properties of the heating pipe, and all these may be helpful to develop a perfect vacuum insulated heating pipeline product.

6. ACKNOWLEDGEMENTS

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