STM JOURNALS

Research & Reviews: Journal of
Physics

https://journals.stmjournals.com/rrjophy

ISSN: 2278-2265 (Online)
ISSN: 2347-9973 (Print)
Volume 14, Issue 3, 2025
September–December
DOI (Journal): 10.37591/RRJoPHY

Review RRJoPHY

High Grade Nuclear Heat Supply from Molten Salt Reactors Via Pipelines: Parametric Studies on Heat Loss Characteristics and Optimal Line Sizing

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Abstract

Nuclear power plants based on molten salt technology have the potential to supply low-carbon-emissions-intensity thermal energy and electricity, thereby supporting industrial decarbonization and reducing reliance on fossil fuels. The primary coolant of these reactors is a multi-component fluoride salt, such as FLiNaK, which exhibits excellent thermal stability and heat transfer properties. This molten salt stream can be partially extracted to serve as an industrial heat source, providing temperatures in the range of approximately 550–600°C, suitable for various high-temperature industrial processes. This study examines the feasibility of pipeline-based transport of this heat source to potential points of use located between 1.6 and 5 km from the reactor. The research estimates heat loss characteristics as a function of pipeline design parameters, insulation type, and transport distance. Heat losses are found to range between 1.5 and 3.5% for a distance of 1.6 km and between 2 and 10% for a distance of 5 km. Additionally, the study determines the optimal pipe diameter that minimizes the combined upfront capital investment and ongoing operating costs, which include pumping energy losses due to fluid friction and heat losses during transport. A dimensionless indicator is used as the objective function for this optimization. The results also indicate that maintaining an optimal molten salt velocity of approximately 3.15 m/s in the pipeline is crucial for minimizing both capital and operational expenditures. These findings provide critical guidance for the design of molten salt heat transport systems, ensuring efficient energy delivery, economic feasibility, and support for industrial decarbonization initiatives.

Keywords: Heat loss, heat transport, molten salt, nuclear reactor, optimal line sizing

INTRODUCTION

Molten salt nuclear reactors (MSRs) represent one of the several advanced nuclear reactor technologies (i.e., Gen-IV reactor concepts) with enhanced safety features, potentially simpler design, capable of producing electricity efficiently, supporting industrial thermal energy demand by supplying high-grade, low-carbon emissions intensity heat and generating less nuclear waste, and promoting more sustainable nuclear energy production and utilization. It is one of the candidate technologies that can enable the utilization of thorium for nuclear power production, as a way to diversify the current uranium-based nuclear fuel cycle and nuclear fuel sources [1]. These reactors can have molten fuel salts in circulation and transfer the heat released from nuclear fission to a primary coolant, which is also a molten salt with no nuclear fuel or fissile material in it. These reactors are thus capable of supporting a wider range of non-electric applications of nuclear power and nuclear

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Received Date: August 27, 2025
Accepted Date: September 20, 2025
Published Date: October 04, 2025

Citation: Rupsha Bhattacharyya. High Grade Nuclear Heat Supply from Molten Salt Reactors Via Pipelines: Parametric Studies on Heat Loss Characteristics and Optimal Line Sizing. Research & Reviews: Journal of Physics. 2025; 14(3): 1–9p.

cogeneration projects for industrial decarbonization, especially those requiring high-temperature heat streams [2–4], than are possible with the current generation of water-cooled reactors.

Heat transfer studies in molten salt have been widely reported in literature, especially physical property data, heat transfer, and pressure drop correlations for different salts in different flow geometries [5–7]. However, their use in studying pipeline-based nuclear heat transport with flowing molten salts has not been studied widely. This gap area is addressed in this work using a simple mathematical model based on heat loss and pressure loss characteristics of molten salt flows in circular pipelines over different transportation lengths. The aim is to determine the optimal line diameter and velocity for transporting heat at a certain volumetric flow rate over a given distance and with a given pipeline insulation thickness. This is, therefore, an extension of the economic line sizing problem for fluid transport in the non-isothermal applications. The broad motivation is to develop an analytical framework for a preliminary assessment of the major factors affecting heat losses, optimal transport distances, and pipeline sizing for molten salt-based nuclear heat transport pipelines.

DATA AND MATHEMATICAL MODEL

Heat Loss and Pressure Drop Calculations

For the molten salt-based thermal energy delivery system, let the pipe inside diameter be D_i m, the outside diameter be D_o, and the length be L m. The fluid volumetric flow rate is Q m^3/s; thus, the linear velocity v in the pipe (in m/s) is:

$$v = \frac{Q}{\pi \times 0.25 \times D_i^2} \tag{1}$$

The pipeline material has thermal conductivity k_w W/m K, and it has insulation of diameter D_{ins} all over the length, with a material of thermal conductivity k_{ins} W/m K. For heat loss estimation with correction for the temperature-dependent fluid physical properties, the pipeline of length L is divided into N elements of equal length, i.e., L/N m each. The thermal energy balance, expressing temperature change in terms of thermal energy loss over the ith element of the pipeline, is written as:

$$U_o A_o ((T(i) + T(i+1)) \times 0.5 - T_\infty) = \dot{m} C_p (T(i) - T(i+1)) \tag{2}$$

The arithmetic mean temperature of the fluid in the pipe segment is used in Eq. (2), while T_∞ represents the ambient temperature.

The overall heat transfer coefficient U_o is expressed as:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{A_o}{A_i h_i} + \frac{D_o \ln \frac{D_o}{D_i}}{2\pi k_w} + \frac{D_o \ln \frac{D_{ins}}{D_o}}{2\pi k_{ins}} \tag{3}$$

The inside heat transfer coefficient, h_i, for the molten salt is estimated from the correlation [5]:

$$Nu = \frac{h_i D_i}{k} = 0.024 Re^{0.807} Prs^{0.301} \tag{4}$$

The outside heat transfer coefficient, h_o, due to natural convection, is not explicitly estimated but is taken to have a typical value between 3 and 10 W/m^2 K (i.e., corresponding to stagnant air) [8].

The temperature at the outlet of each pipe segment is calculated, and the calculations are repeated to finally arrive at the pipe outlet temperature. Physical property data that are a function of temperature are updated once the fluid temperature in each segment is calculated.

If the pipe inlet temperature is T_{in} and the outlet temperature is T_{out}, the total heat loss from the pipe is expressed in terms of a percentage value of the incoming enthalpy of the molten salt stream (assuming the enthalpy to be only temperature dependent) as:

$$\%Q_{loss} = \left(\frac{T_{in} - T_{out}}{T_{in}}\right) \times 100 \tag{5}$$

The frictional pressure loss over the transport length is calculated based on the friction factor f, whose calculation process is described by Kolev for different ranges of values of Reynolds Number Re [9]. Once the friction factor is established, the frictional head loss (in m of the flowing molten salt) is given by:

$$\Delta P_{\mathrm{fric}} = f\frac{L}{D_i}\frac{v^2}{2g} \tag{6}$$

Optimal Line Sizing Methodology

For optimal line sizing for thermal energy transport applications, three principal factors are considered: the capital cost of the pipeline, the operating cost of fluid transport, and the penalty due to heat losses. Each of these factors has to be minimized.

If capital cost is directly proportional to the pipeline material cost and weight of the pipeline, then it can be written that:

$$\mathrm{capex} \propto \pi D_i t L \times W_l \tag{7}$$

Here, W_l refers to the weight per unit length of the pipe, for a fixed pipeline material.

The operating cost, i.e., fluid pumping cost, is directly proportional to head loss when volumetric flow rate is kept constant; therefore,

$$\mathrm{opex} \propto \Delta P_{\mathrm{fric}} \propto f\frac{L}{D_i}\frac{v^2}{2g} \tag{8}$$

The heat loss is directly proportional to the pipe's outermost surface area; therefore,

$$Q_{\mathrm{loss}} \propto \pi(D_i + 2 * t + 2 * t_{\mathrm{ins}})L \tag{9}$$

Thus, each of the terms is expressed as a function of the pipe inside diameter. Each of the three terms should be as less as possible, and the optimal value of D_i would be such that the combination of these three terms would be minimum. A search-based technique is used to identify this optimal value of D_i, for a given set of parameters, considering each of the factors to be optimized as an independent criterion, but each being a function of D_i.

Let for a set of p chosen pipe diameters D_i in an applicable range of values, each of the three terms is calculated. This gives us a set of p-values of capex values, opex values, and Qloss values, corresponding to each diameter value tested. Let normalized values for each of these terms be given by three indicators, C_1, C_2, and C_3, respectively, where,

$$C_1(i) = \frac{\mathrm{capex}(i)}{\max(\mathrm{capex})},$$

$$C_2(i) = \frac{\mathrm{opex}(i)}{\max(\mathrm{opex})},$$

$$C_3(i) = \frac{Q_{loss}(i)}{max\,(Q_{loss})}, \quad i \in [1, p] \tag{10}$$

This helps avoid the explicit evaluation of the proportionality constants in the Eqs. (7)–(9). Thus, a composite, additive, dimensionless indicator KI, which is a function of D_i, may be defined for every D_i value as:

$$\mathrm{KI}(i) = C_1(i) + C_2(i) + C_3(i) \tag{11}$$

The optimal line size D* is the one that minimizes the value of KI. This can therefore be considered an optimization routine based on relative values of the objective function rather than the absolute, where each component of the objective function has been assumed to have equal importance or weightage. Once D* is determined, the optimal molten salt velocity in the pipeline can also be calculated using Eq. (1).

Table 1. Input data for parametric studies on heat loss and optimal line sizing.

Parameter	Value	Remarks
Pipe material of construction	Hastelloy N	Identified to be most compatible in molten salt service from a corrosion resistance point of view [10]
Volumetric flow rate	0.025 m^3/s	A reference value is chosen for analysis
Range of pipeline diameter considered	0.075 to 0.18 m	Depending on the chosen volumetric flow rate, the velocity is kept between 1 to 5 m/s as typical values for molten salt heat transfer cases, and the diameter is selected accordingly [11]
Pipe surface roughness	5.4×10^{-4} m	Typical value for commercial metallic pipelines
Fluid	FLiNaK	Identified as a good candidate for molten salt for coolant service in molten salt reactors [12]
Fluid density	2729.3–0.73T kg/m^3	Expression reported in literature [5–7]
Fluid viscosity	$2.487\times10^{-5}\exp(4478.62/T)$ Pa s	Expression reported in literature [5–7]
Fluid thermal conductivity	$0.36+5.6\times10^{-4}T$ W/m.K	Expression reported in literature [5–7]
Fluid specific heat capacity	976.8+1.0634T J/kg.K	Expression reported in literature [5–7]
Fluid inlet temperature	873 K	Value selected to be well above the melting point of the coolant salt (i.e., above ~450°C/723 K) to prevent salt solidification and choking anywhere in the transport line [12]
Pipeline material thermal conductivity	23.6 W/m K	Value reported in industrial literature
Pipe wall thickness	0.01 m	Corresponding to the standard pipe diameter, Schedule 80 pipe is chosen for this service, and the wall thickness is accordingly decided.
Insulation material thermal conductivity	0.12 to 0.22 W/m K	Typical value for high-temperature ceramic fibre insulator materials for pipelines is used in this analysis.
Insulation layer thickness and ambient temperature	1 in/0.0254 m, 300 K	A typical value of thickness is chosen for analysis; it is varied between 0.5 and 2 in for parametric sensitivity analysis.
Length of pipeline/ heat transportation distance	1.6 to 5 km	The minimum value of 1.6 km corresponds to the typical exclusion zone dimension for a nuclear reactor; the end user of the nuclear heat transported by the molten salt stream cannot be located closer than this distance to the reactor, so this is a minimum heat transport distance.

The required data for performing the calculations described in this section are shown in Table 1. Temperature-dependent fluid properties are used for calculations.

RESULTS AND DISCUSSION

This section presents the key results from the analysis described earlier, along with a corresponding discussion of the significance of the findings.

Heat Loss and Pressure Drop Characteristics in Molten Salt Transport Lines

Figure 1a shows the linearly increasing heat loss with increasing pipeline diameter for a given insulation thickness and pipeline length. With 1 in insulation thickness, the heat loss over a 1600 m pipeline is only about 1.2–2.8% of the incoming thermal energy carried by the molten salt stream. This is due to the linearly rising surface area available for convective heat loss from the molten salt as the pipe diameter increases, with a constant thickness insulation layer applied over it.

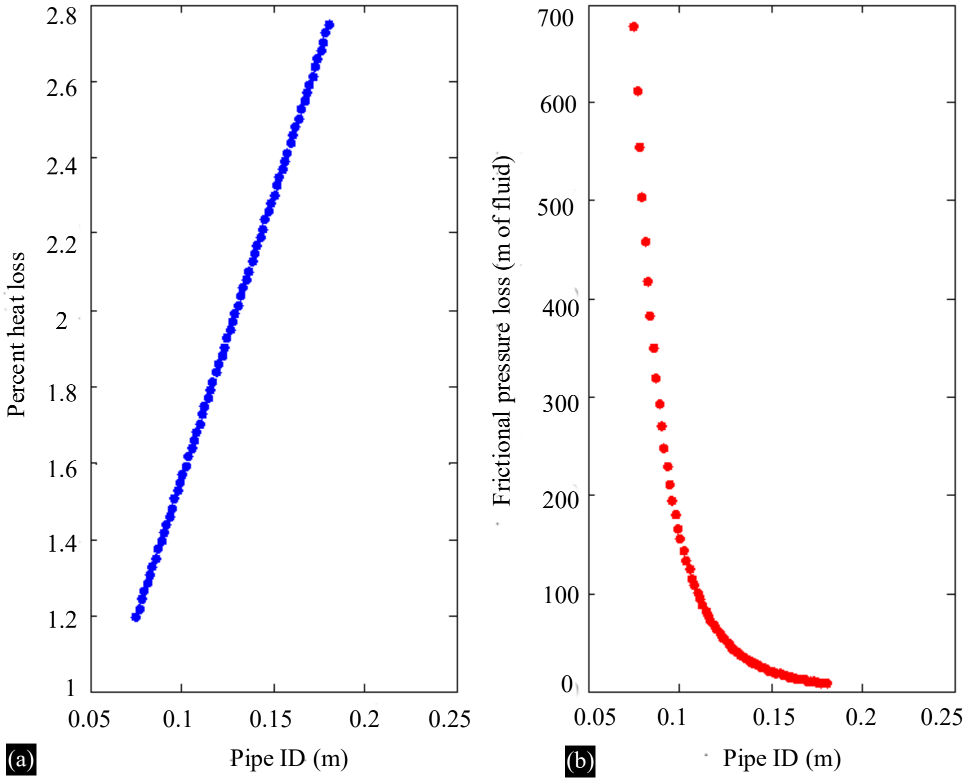

Figure 1. (a) Heat loss and (b) pressure drop of molten salt as a function of pipe diameter over a pipeline length of 1600 m.

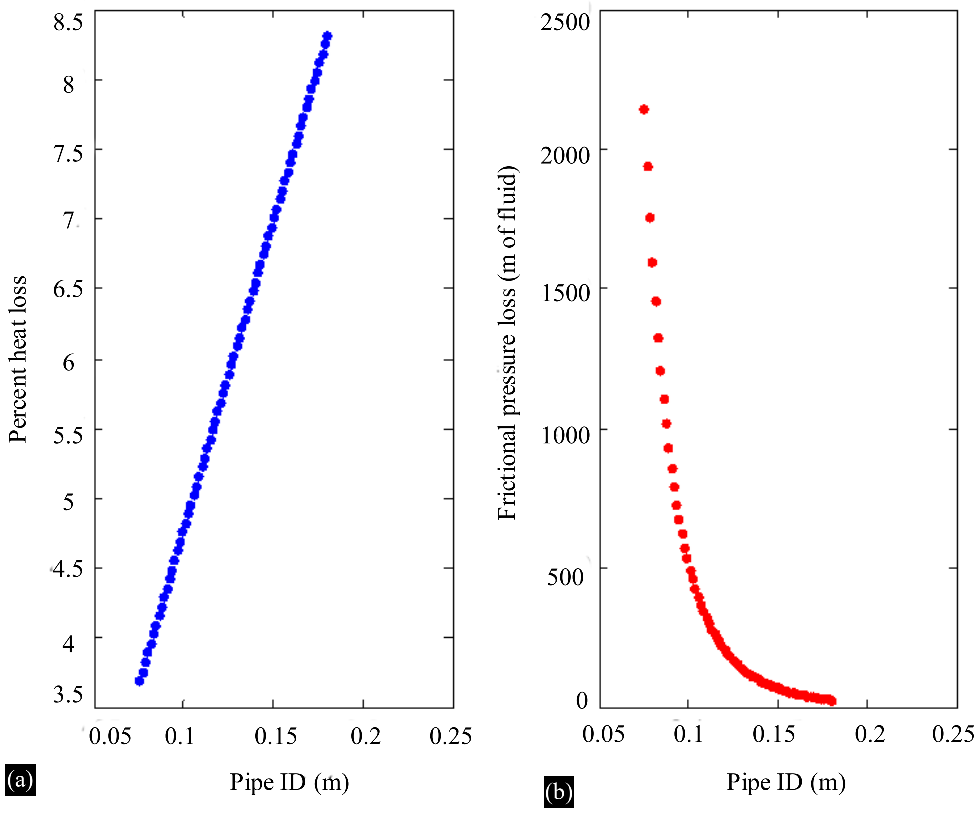

Figure 2. (a) Heat loss and (b) pressure drop of molten salt as a function of pipe diameter over a pipeline length of 5000 m.

Figure 1b shows the sharply declining frictional pressure drop as a function of pipeline diameter, when line length is kept constant. This is due to the $1/D_i^5$ dependence of head loss on pipe diameter, as can be observed from Eq. (6). Thus, for a given pipeline length, there is a tradeoff between rising heat loss with diameter and falling pressure drop with diameter, indicating the existence of an optimum diameter.

Figure 2(a) and (b) shows similar gross heat loss and pressure drop characteristics as in Figure 1(a) and (b), for a pipeline of length 5000 m, with corresponding differences in numerical values of the quantities involved. Thus, it is seen that an optimal diameter exists in this case also.

Optimal Line Sizing and Parametric Sensitivity Studies

Figure 3 shows that over a molten salt transport length of 1600 m, the optimal diameter is about 0.1 m, at which the molten salt velocity is 3.15 m/s. The heat loss is 1.57% of the entering thermal energy carried by the flowing salt, and this leads to a temperature drop of 13.7 K across the length of the pipeline. For a pipeline length of 5000 m, the values are found to be 0.1 m, 3.15 m/s, 4.83% and 42 K, respectively. Thus, optimal pipe diameter is independent of pipeline length, for given insulation thickness and insulation type. The Reynolds Number, Prandtl Number, and Nusselt Number for the molten salt under this optimal condition are approximately 1.46×10^5, 10.26, and 711, respectively, showing that the flow inside the pipe is highly turbulent under these operating conditions. Figure 4 shows the negligible influence of insulation thickness on optimal diameter, for a given pipeline length and insulation thickness.

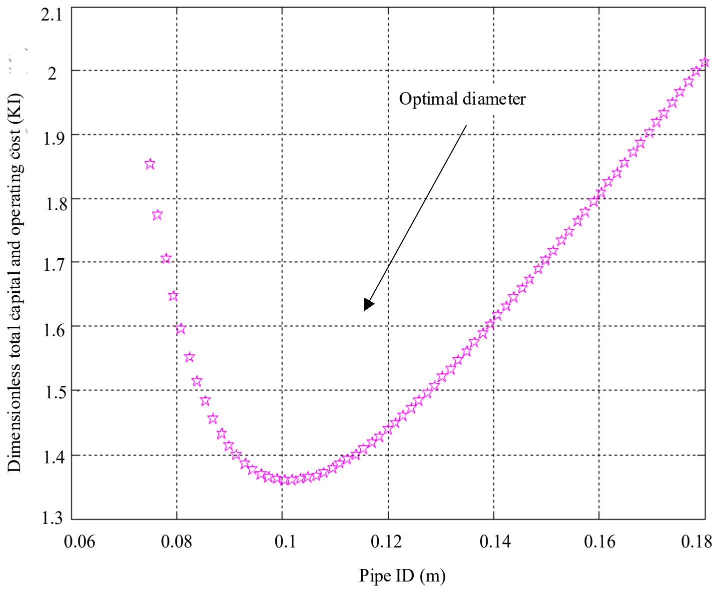

Figure 3. Determination of optimal diameter of molten salt heat transport pipeline (1.0-inch-thick insulation, thermal conductivity =0.12 W/m.K).

Figure 5 shows the simultaneous effect of changing insulation thickness and pipeline length on heat loss characteristics, when the pipeline diameter is kept constant. The use of these results can be made in the following manner. For example, to limit heat losses to 5% with an insulation thickness of 0.5 in over a pipeline having an inside diameter of 0.1 m, the transport distance should not be greater than 2.5 km. The effect is nearly linear, and this analysis can be extended to distances beyond 5 km as well. Therefore, this graph is useful as a guide or a look-up graphic to rapidly estimate the upper limit of the thermal energy end user's distance from the nuclear power plant based on a certain allowed percentage heat loss for a given thickness of insulation and pipe diameter. Figure 6 shows the effect of thermal conductivity of insulation material on heat losses over various distances. With a 1.83 times increase in insulation conductivity (due to a difference in insulation density), a nearly proportional heat loss is seen over the same distance with the same pipe diameter and insulation thickness. Thus, insulation selection has the greatest influence on heat losses taking place from the heat transport pipeline.

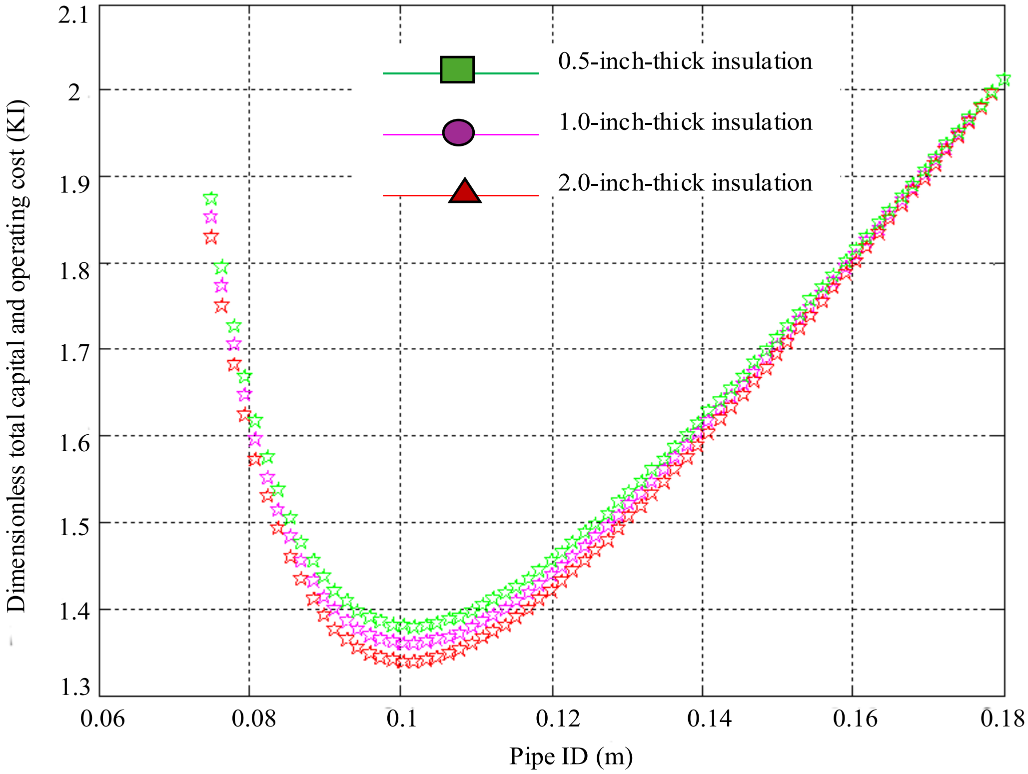

Figure 4. Effect of insulation thickness on optimal pipeline diameter.

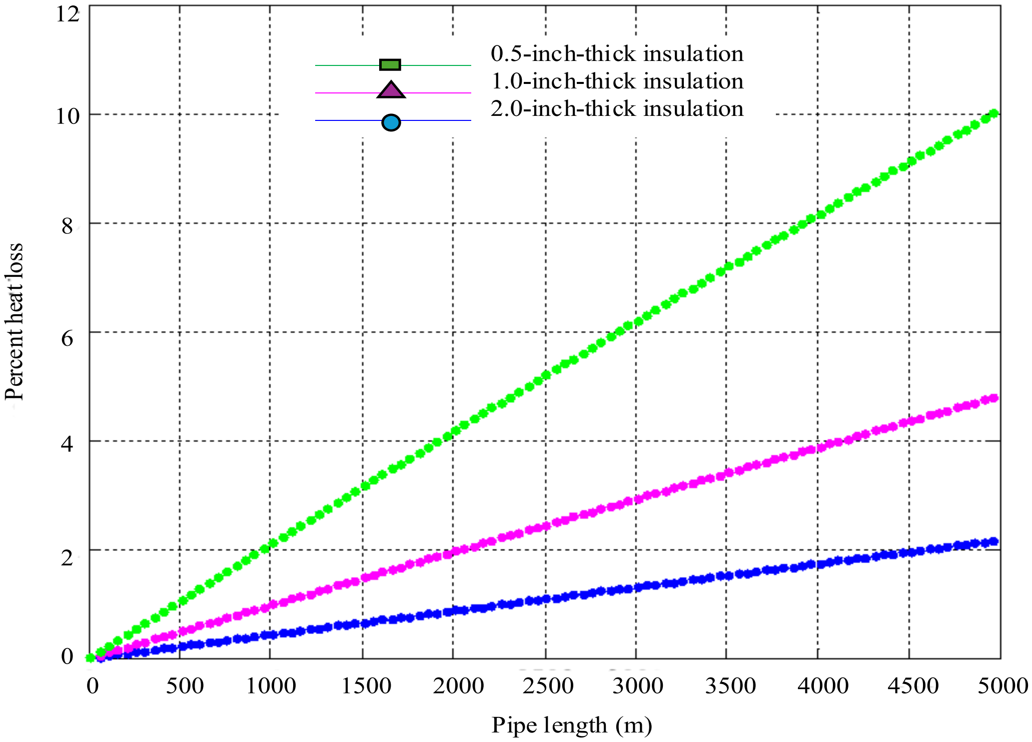

Figure 5. Effect of insulation thickness and pipeline length on heat loss characteristics (optimal pipeline diameter =0.1 m, insulation thermal conductivity =0.12 W/m.K).

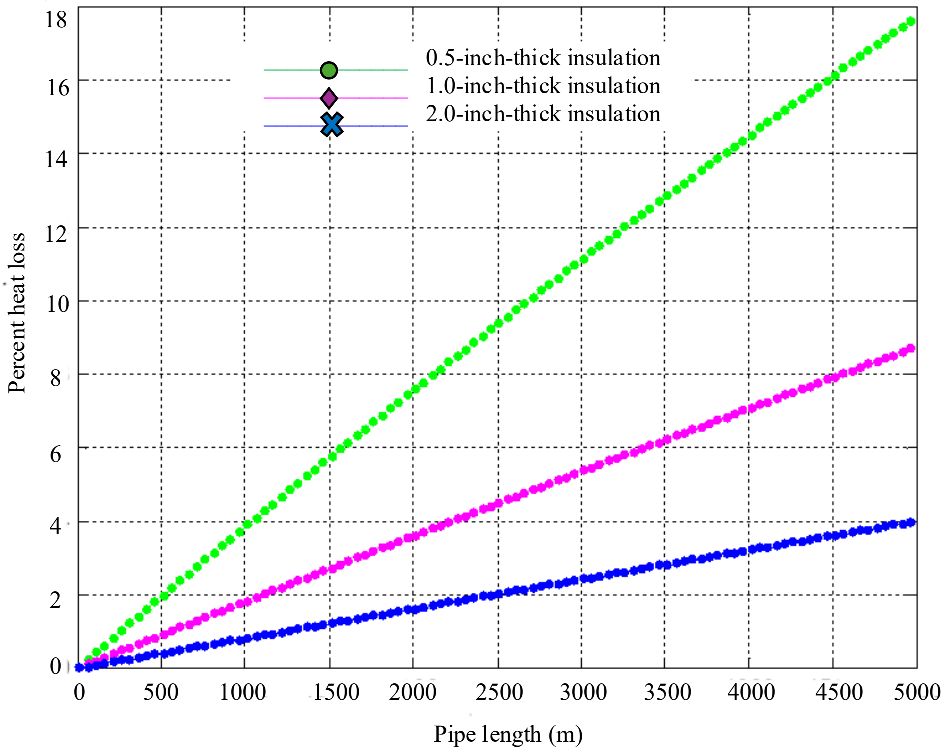

Figure 6. Effect of insulation thickness and pipeline length on heat loss characteristics (optimal pipeline diameter =0.1 m, insulation thermal conductivity =0.22 W/m.K).

CONCLUSION

The present study is an analysis of heat loss and pressure drop characteristics of molten salt transportation pipelines for high-grade nuclear thermal energy transport using molten salt to those industrial end users requiring high-temperature heat for their operations. Transportation distances of 1.6 to 5 km have been considered, with FLiNaK molten salt transportation pipelines having diameters such that fluid velocity is kept between 1 and 5 m/s.

The key findings from this study are the following:

1. Considering the tradeoff between pipeline capital cost, pressure drop, and heat loss, the optimal fluid velocity is found to be 3.15 m/s; this helps calculate the optimal pipe diameter for a given throughput of fluid. In this study, the optimal diameter is found to be about 0.1 m for a throughput of 0.025 m^3/s of molten salt at 873 K.
2. The value of the Reynolds Number at optimal conditions is found to be about 1.46×10^5 for the molten salt analyzed here.
3. The thermal energy loss is estimated to be between 1.5 and 3.5% for a distance of 1.6 km and between 2 and 10% for a distance of 5 km, depending on insulation type (commercially available ceramic wool high temperature insulator considered in this work) and thickness (values between 0.5 and 2 in have been considered in this work). The loss up to distances of 1.6 km can be considered acceptable for industrial application scenarios.

The study may be further extended to evaluate the flow and heat transfer characteristics with (i) other possible molten salts for high-temperature heat transport applications, (ii) other insulating materials, and (iii) other ranges of flow conditions to determine the optimal line size in each case. The use of intermediate heat exchangers to transfer the primary heat from the reactor core to the secondary side and then to the industrial heat demand center can also be considered. Detailed techno-economic studies can also be carried out to evaluate the actual levelized costs of transporting nuclear heat over different distances using different molten salts for various end users.

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