EuroSun2026

MEASUREMENT SYSTEM DESIGN FOR THE EXPERIMENTAL EVALUATION OF HIGH-VACUUM MULTILAYER INSULATION IN MID-TEMPERATURE APPLICATIONS

Summary

This work investigates the thermal performance of High-Vacuum Multilayer Insulation (HVMLI) for Heat Transfer Fluid pipelines in the 100–250 °C range. A measurement system based on the Hot Guarded Pipe method was designed and developed for the experimental characterization of two HVMLI configurations with one and ten aluminium layers. Tests were carried out under high-vacuum conditions and compared with analytical predictions. Both configurations showed thermal conductivity values at least one order of magnitude lower than conventional rockwool insulation, while the 10-layer solution achieved a further 1.5-fold improvement over the single-layer one.

Keywords: High Vacuum, Multilayer Insulation, Guarded Hot Pipe, Measurement System

Field of application for the findings: Solar thermal fields, Thermal energy storage and distribution

Addressed audience: Researchers, engineers, and industry professionals in solar thermal energy

1. Introduction

Thermal insulation plays a crucial role in reducing heat losses within energy systems. Improved insulation enhances system efficiency and supports decarbonization efforts (Lund and Mohammadi, 2016). In solar thermal applications, insulation is particularly important for energy storage, where improved thermal performance allows longer storage times, as in sensible and latent heat storage systems (Villasmil et al., 2019). In solar thermal plants, each component should be optimized; therefore, effective insulation of Heat Transfer Fluid (HTF) pipelines contributes to improving the overall system efficiency. Proper pipeline insulation is essential to maintain a uniform HTF temperature along distribution networks and to minimize thermal losses (Ucar and Balo, 2009).

Vacuum insulation offers the best insulation performance by suppressing convection and limiting conduction through residual gases. In this context, High-Vacuum Multilayer Insulation (HVMLI) technique employs low-emittance layers around the pipeline, thereby significantly reducing radiative heat transfer (Bapat et al., 1990). This technology is well established in cryogenic applications (temperatures below −150 °C), where thermal conductivity k values can be as low as 10^{-5} $Wm^{-1}K^{-1}$, as measured by standardized boil-off calorimetry (Fesmire and Johnson, 2018).

However, in the mid-temperature range, insulation performance is commonly characterized using the Hot Guarded (HG) method (Selzer et al., 2009). The application of HVMLI introduces additional challenges for HG-based measurements, primarily because the substantially reduced heat transfer complicates accurate characterization.

This work investigates the design of a measurement system based on the HG method for evaluating HVMLI performance between 100 °C and 250 °C. The thermal analysis conducted on the proposed architecture provides the parameters required for the construction of an experimental setup. Thermal tests are performed on two HVMLI configurations employing, respectively, a single aluminium layer (1-Al) and ten aluminium layers (10-Al). The performance of the two is evaluated using the HGP method and compared with the theoretical values.

2. Design and Thermal Analysis

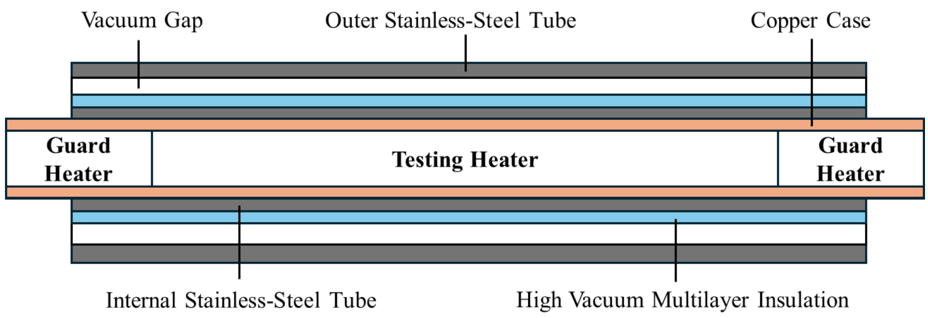

Figure 1 – Architecture design of the experimental setup with the Hot Guarded Pipe method implemented in a vacuum chamber equipped with a High Vacuum Multilayer Insulation.

Figure 1 shows the architecture of the proposed experimental setup designed to evaluate the performance of the two HVMLI configurations. An inner stainless-steel tube is wrapped with aluminium layers arranged in a spiral configuration. High vacuum is established in the gap between the inner stainless-steel tube and the outer stainless-steel tube. The heater used for HGP measurements is divided into three sections: the central section acts as the test heater. The two lateral sections act as guard heaters, preventing heat dissipation in the axial direction and thereby improving the resolution of the heat transfer measurement in the radial direction.
Figure 2 shows the main results of the thermal analysis conducted on the proposed architecture to define the geometrical properties of the experimental setup and the proper measurement chain. The left y-axis reports the radiative heat loss as a function of the axial length of the prototype for three different inner diameters (solid lines), calculated according to radiative screen theory. For an equivalent thermal emittance of ε_{eq} = 0.005, representative of a 10-layer aluminium configuration, a prototype length of 1 m results in a thermal loss of at least 0.5 W for diameters of 50 mm and 100 mm. The right y-axis reports the ratio between axial and radial thermal losses (dashed and dotted lines), which represents the maximum resolution ensured by the system. The axial thermal loss is due to heat conduction through the annular section of the inner tube. The results show that, for a 1 mm thick stainless-steel tube, a length of approximately 1.5 m is required to reduce the axial thermal loss to a negligible value below 1% of the radiation.

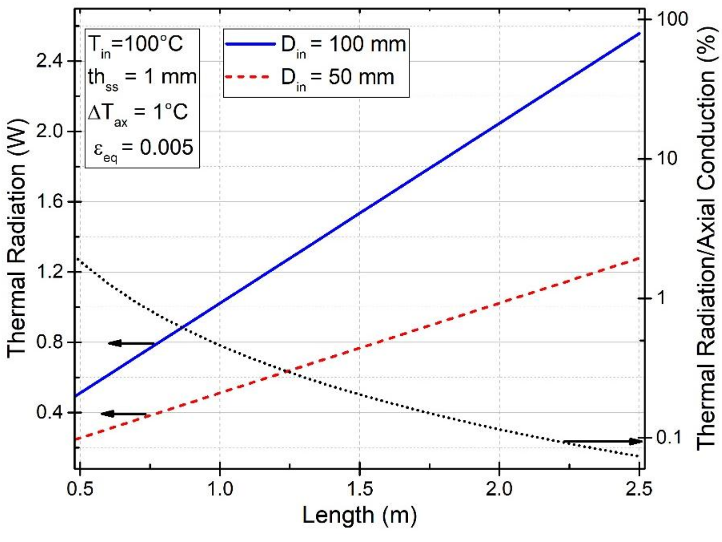

Figure 2 – Left axis: thermal radiation as a function of the length for two different outer diameters of the inner tube: 100 mm (blue solid line) and 50 mm (red dashed line). Right axis: ratio between the thermal radiation and the axial conduction as a function of the length (black dot line).

3. Experimental Results

The design and thermal analysis of the proposed architecture provided the key parameters for the development of the experimental setup. It consists of a welded concentric-tube configuration made of two stainless-steel tubes. The inner tube has a length of 1.4 m, an outer diameter of 54 mm, and a thickness of 1.5 mm, in accordance with commercial standards for heat transfer fluid pipelines. The length and diameter were selected based on the results presented in Figure 2. The tube thickness represents a trade-off between reduced axial heat conduction and sufficient mechanical resistance to withstand the pressure differential between ambient pressure and high-vacuum conditions.

Thermal tests were conducted using the HGP method on two different configurations. The first solution employs a single 15 μm-thick aluminium layer, whereas the second employs 10 aluminium layers, each 30 μm thick, arranged in a spiral configuration. The results of the experimental campaign are summarized in Figure 3. All measurements were carried out with a pressure in the annular gap below 10^{-3} Pa (10^{-5} mbar), ensuring high-vacuum conditions throughout the entire test campaign, and with an axial temperature difference ΔT below 1 °C, in accordance with one of the HGP design criteria adopted for the setup.

Both tested HVMLI configurations exhibited *k* values at least one order of magnitude lower than those of rockwool, which is the current standard insulation solution for this temperature range. The 1-Al configuration shows good agreement with the analytical model. The 10-Al configuration further improves the thermal performance of the 1-Al design, exhibiting *k* values 1.5 times lower.

The discrepancy between the analytical predictions and the experimental results suggests two possible explanations:

- The resolution of the experimental apparatus is not high enough to ensure reliable measurement of thermal conductivities below 10^{-3} $Wm^{-1}K^{-1}$.
- Radiative screen theory alone is insufficient to describe the physical behaviour of HVMLI as additional heat transfer mechanisms may occur.

Further developments will focus on the design of a dismountable vacuum chamber to obtain an experimental setup that allows different HVMLI configurations to be tested more easily to identify the most effective solution. At the same time, the setup will be equipped with additional sensors to investigate other physical mechanisms, such as residual gas conduction.

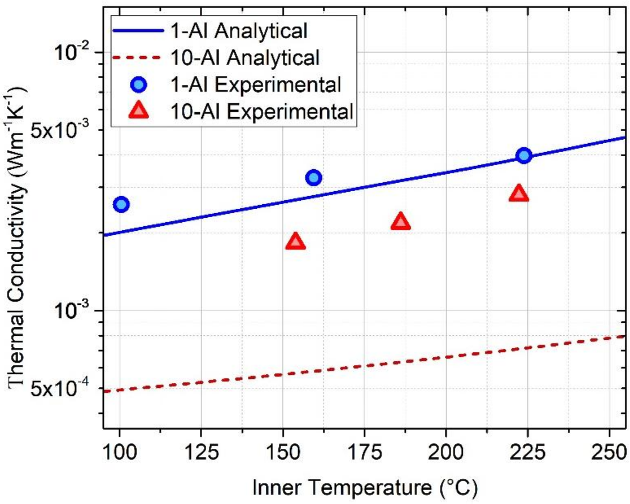

Figure 3 – Thermal conductivity as a function of the inner temperature. Curves represent the analytical trend for the 1-Al insulation (blue solid) and the 10-Al (red dashed). Scatters represent the experimental points for the 1-Al (blue circles) and the 10-Al insulation (red triangles).

4. References

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