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THERMAL PERFORMANCE OF CRYOGENIC PIPING MULTILAYER INSULATION IN ACTUAL FIELD INSTALLATIONS

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ABSTRACT

A standardized way of comparing the thermal performance of different pipelines in different sizes is needed. Vendor data for vacuum-insulated piping are typically given in heat leak rate per unit length (W/m) for a specific diameter pipeline. An overall k-value for actual field installations (k_{oafi}) is therefore proposed as a more generalized measure for thermal performance comparison and design calculation. The k_{oafi} provides a direct correspondence to the k-values reported for insulation materials and illustrates the large difference between ideal multilayer insulation (MLI) and actual MLI performance. In this experimental research study, a section of insulated piping was tested under cryogenic vacuum conditions, including simulated spacers and bending. Several different insulation systems were tested using a 1-meter-long cylindrical cryostat test apparatus. The simulated spacers tests showed significant degradation in the thermal performance of a given insulation system. An 18-meter-long pipeline test apparatus is now in operation at the Cryogenics Test Laboratory, NASA Kennedy Space Center, for conducting liquid nitrogen thermal performance tests.

INTRODUCTION

Ambient heat transfer into a cryogenic pipeline comes through several paths including valves, connectors, instrumentation, and insulation. A common type of thermal insulation system is MLI. MLI systems come in many varieties and must be tailored to the specific application. As reviewed by Augustynowicz and Fesmire (2000), the performance of MLI is known to be sensitive to localized compression effects and trapped residual gases produced by the combined mechanical influences of bending and spacers. Bending-type mechanical effects come from four sources: bending, as in handling and installation; thermal contraction and expansion; line pressure reaction forces; and the weight of the line (sagging). Spacers are employed in the design of vacuum-jacketed lines to keep the inner line concentric within the outer line during manufacturing and to counteract these mechanical effects during operation. Spacers are made from low-thermal-conductivity materials to minimize heat conduction. In this experimental research study, a section of insulated piping was tested under cryogenic vacuum conditions including simulated bending and spacers.

1. THERMAL INSULATION SYSTEM OVERALL PERFORMANCE

In reality no one really needs insulation. What is important is to save money on the energy bill or to be able to effectively control a system. Thermal insulation systems therefore provide energy conservation and allow system control for cryogenic process systems.

The overall efficiency is governed by four basic factors: 1) thermal conductivity, 2) vacuum level, 3) density or weight, and 4) cost of labor and materials. The vacuum level is the major cost driver for systems that must operate under the high vacuum condition. A material's thermal conductivity is described in terms of milliwatt per meter-kelvin (mW/m-K) for a small difference in boundary temperatures. An insulation material's performance under a large temperature difference is also measured in terms of mW/m-K but is referred to as an apparent thermal conductivity or k-value. Finally, the performance of a total thermal insulation system as it is actually deployed in use is defined as the overall k-value for actual field installation or k_{oafi} (Fesmire *et al.*, 2001). The total system includes the inner piping, the insulation material layers, the outer piping, and other items such as spacers and getters. Geometry, spacer design, manufacturing factors, vacuum maintenance, outgassing, insulation materials, layer densities, and other factors all affect the overall thermal performance of a double-walled piping system.

The performance of MLI systems varies widely. Augustynowicz *et al.* (2000) assert that there are three levels of thermal performance of MLI: ideal, laboratory, and industrial. Ideal performance using advanced materials and sophisticated technique can approach 0.01 mW/m-K while the laboratory performance using state-of-the-art methods will be around 0.1 mW/m-K. Industrial performance, including the effects of spacers and bending, is then in the range of 1 mW/m-K as evidenced by vendor data and practical experience. This study provides some quantitative data to assess this wide range of performance.

2. TEST RESULTS AND DISCUSSION

The experimental apparatus and methods of the liquid nitrogen cryostat have been previously described by Fesmire *et al.* (2001) and Fesmire and Augustynowicz (2000).

All MLI test articles are comprised of the standard aluminum foil and fiberglass paper arrangement. Test article C108 is 40 layers at a density of 1.8 layers/mm while test article C123 is 60 layers at a density of 2.4 layers/mm. Test article C124 is actually the same as C123 but with the addition of five circumferential rings. These 6.4-mm plastic rings were installed at a spacing interval of 102 mm to simulate the compression effect of spacers in a double-wall cryogenic pipeline construction. The compressed local density was measured to be 8.4 layers/mm (or 71 percent compression). The results of the simulated spacers test are given in Figure 1. The spacer simulation shows a significant increase in the rate of heat transfer for the high-vacuum tests. For C123 in comparison to C124 the k-value increased from 0.09 to 0.15 mW/m-K (a 67 percent increase in heat transfer).

Vendor data for vacuum-insulated piping are typically given in heat leak rate per unit length (W/m) and are useful then only for a specific diameter pipeline. The k_{oafi} is therefore given as a more generalized measure for thermal performance comparison and design calculation. For example, from a previous study of a 200-mm by 254-mm double-walled flexible pipe

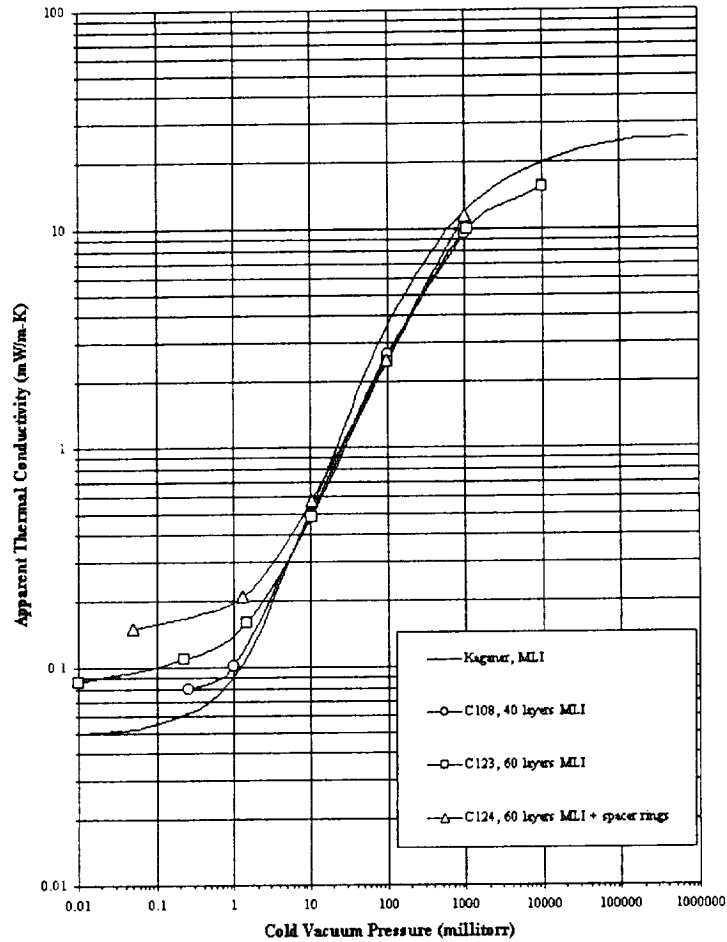


Figure 1. Variation of apparent thermal conductivity with CVP, spacer simulation results.

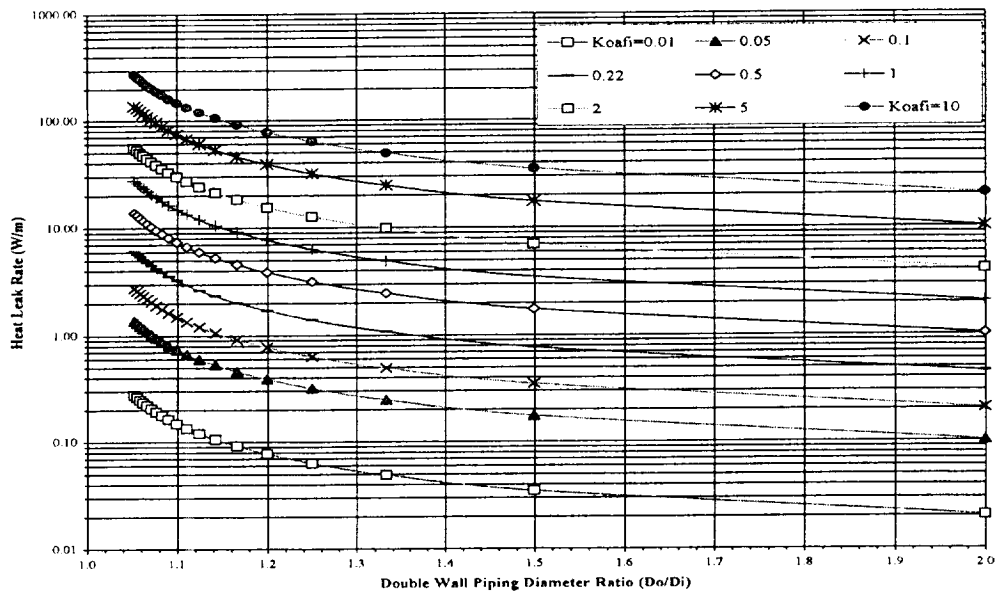


Figure 2. Variation of heat leak rate with diameter ratio (D_o/D_i) for k_{oaf} from 0.01 to 10 mW/m-K and boundary temperatures of 300K and 77K.

with 60 layers MLI, the k-value (at high vacuum with boundary temperatures of 295 K and 105 K) was reported to be about 0.22 mW/m-K. Now consider a 75-mm- by 125-mm-size line operating at boundary temperatures of 300 K and 77 K. The heat leak rate per unit length for this particular case can then be determined by equation (1):

$$\frac{Q}{L} = 2\pi k_{\text{oafi}} \frac{\Delta T}{\ln\left(\frac{D_o}{D_i}\right)} = 2.743k_{\text{oafi}} = 0.60 \text{ W/m} \quad (1)$$

Figure 2 provides a convenient design tool for estimating heat loads (W/m) for different lines sizes and different k_{oafi} . The experimental laboratory data can be compared with manufacturers' typical data for a 60-mm by 110-mm size line: 2.30 W/m (flexible) and 0.75 W/m (rigid). Converting these typical heat leak values into their thermal conductivity equivalents, we obtain k_{oafi} of 0.99 mW/m-K (flexible) and 0.32 mW/m-K (rigid). The k_{oafi} also provides a direct correspondence to the k-values reported for insulation materials and illustrates the large difference between ideal MLI performance and the performance of actual systems with MLI.

CONCLUSION

In this experimental research study, a section of insulated piping was tested under cryogenic vacuum conditions, including simulated spacers and bending. An overall k-value for actual field installation (k_{oafi}) has been defined for direct comparison of different types and different sizes of double-walled insulated piping. The simulated spacers tests showed, at high vacuum conditions, significant degradation in the thermal performance of a given insulation system. The k-values for 60 layers MLI with and without the simulated spacer rings were measured to be 0.15 mW/m-K and 0.09 mW/m-K, respectively. The apparent thermal conductivity value for the ideal MLI under the same high vacuum condition is 0.05 mW/m-K. Considering a 75- by 125-mm-size line, for example, at the same boundary temperatures of 300 K and 77 K, the heat leak rate per unit length is calculated to be 0.41 W/m. This figure for rigid piping can then be compared with vendor data of 0.75 W/m, which corresponds to a k_{oafi} of 0.32 mW/m-K. An 18-m-long pipeline test apparatus is now in operation at the Cryogenics Test Laboratory for conducting liquid nitrogen thermal performance tests. Performance data for a variety of commercial and prototype pipelines are currently being obtained.

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