TEST METHOD FOR MEASURING INSULATION VALUES OF CRYOGENIC PIPES

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ABSTRACT

In this paper a large-area heat flux and temperature sensor (HFT) is used for the evaluation of the insulation value of cryogenic pipes. The HFT is flexible and clamp-on. The test method is relatively simple and can be used in-situ. The HFT makes it possible to monitor insulation performance over elongated times and to study localized effects (thermal bridges).The method complies with the Standard Practice ASTM C 1041 – 85 (2007). The method is originally designed for subsea oil pipelines. Three commercial rigid cryogenic pipes are tested, using vacuum, polyisocyanurate and polyurethane insulation. The method is also used on flexible cryogenic pipes.

INTRODUCTION

An important performance parameter for cryogenic pipes such as used for LNG transport is the thermal insulating value. Poor insulation will result in boil off. Available pipe insulation test methods are used only above room temperature, such as ASTM C335 [1], ASTM C1033 [2] and EN ISO 8497[3]).

Reference [4] describes a cylindrical liquid nitrogen boil off calorimeter with mass flow meters to measure the boil off, for the measurement of the overall thermal conductivity of insulating systems. Though potentially accurate, the method is limited to a lab environment and requires quite some preparation, safety measures and equipment. Alternative boil off measurements by means off weight loss, also is not straightforward when accuracy is required.

In this paper a large-area heat flux and temperature sensor (HFT) is used for the evaluation of the overall insulation value of cryogenic pipes, according to the Standard Practice ASTM C 1041 – 85 (2007) [6]. The HFT is flexible and clamp-on. The HFT is a relatively simple and portable device that can be applied in-situ. The HFT makes it possible to monitor insulation performance over elongated times, i.e. detect insulation degradation due to moisture penetration. Also it possible to measure local insulation values, i.e. the presence of a spacer in a vacuum insulated pipe or the effect of insulation joints (thermal bridges).

The method was originally designed for "simulated service conditions testing" for subsea oil pipelines. The method is used in [7] to study the behavior of thermal insulation coating systems on steel pipe. In this study the pipe is internally heated to temperatures up to 140 °C and subjected externally to hydrostatic pressures up to the equivalent of water depths of 1450 m. Recently the method was used to measure the overall insulation value of flexible cryogenic pipes, consisting of a multilayer of fabrics, plastic sheets and SS coil.

In this paper the insulation value of three commercial rigid cryogenic pipes was measured: polyisocyanurate insulated pipe (=’PI’), polyurethane insulated pipe (=’PU’) and vacuum insulated pipe (=‘VI’), see Figure 1.

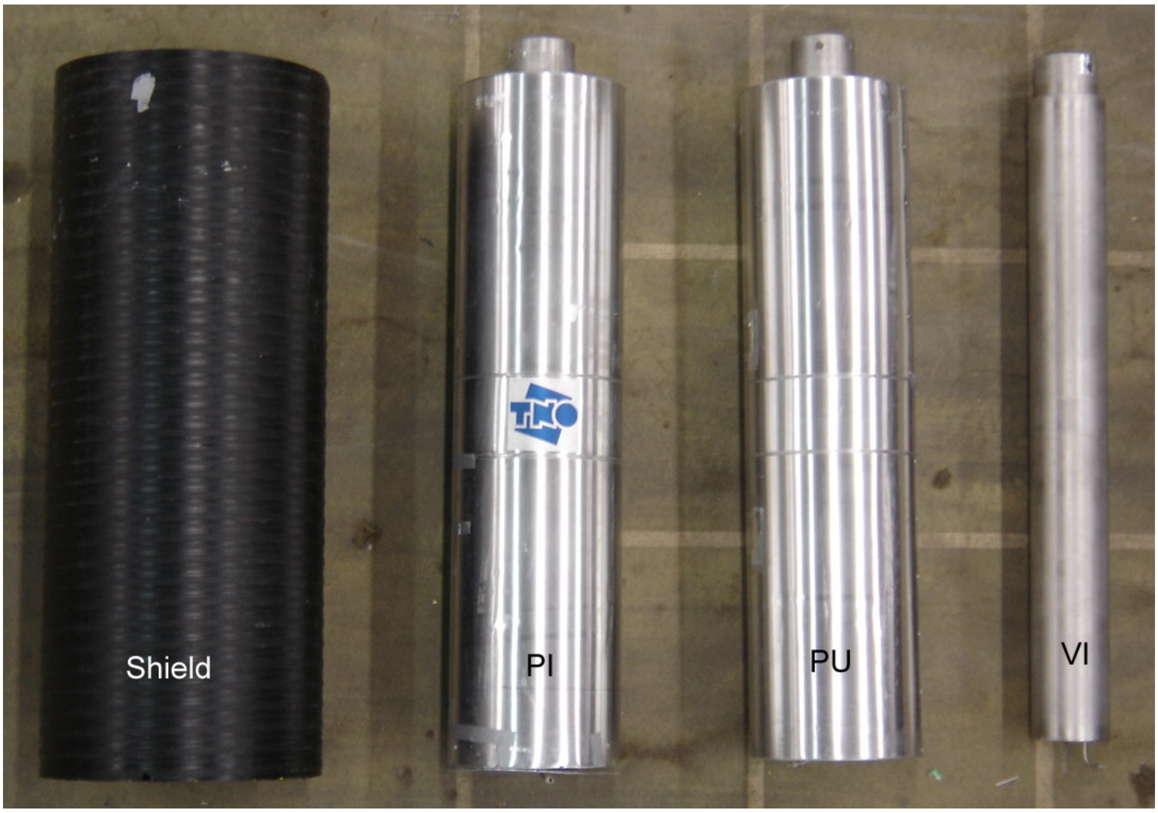


Figure 1. Test pipes: Polyisocyanurate insulated pipe (PI), polyurethane insulated pipe (PU) and vacuum insulated pipe (VI). The Polyethylene (PE) shield is placed around the pipes to damp out climate variations.

HEAT FLUX TRANSDUCERS (HFT)

The HFT used is a large-area flexible heat flux and temperature sensor for in-situ evaluation of the insulation value of pipes, see Figure 2 and Figure 3. The sensor contains three individual heat flux transducers and four temperature sensors. Each heat flux transducer comprises of thermopiles that sense the temperature drop across the transducer, giving a voltage output proportional to the heat flux over the transducer. Table 1 gives typical HFT specifications.

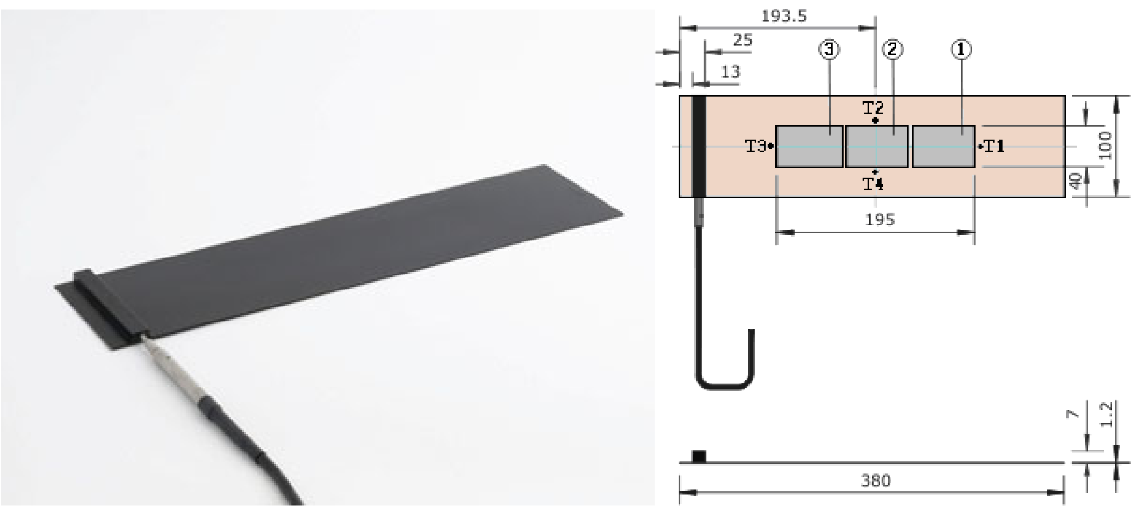


Figure 2. (a) Flexible (HFT) Heat Flux Transducer (TNO). b) HFT comprising of three individual heat flux sensors ‘grey’, numbered ‘1’, ‘2’, ‘3’ and four temperature sensor numbered ‘T1’, ‘T2’, ‘T3’, ‘T4’. Dimensions are shown in mm.

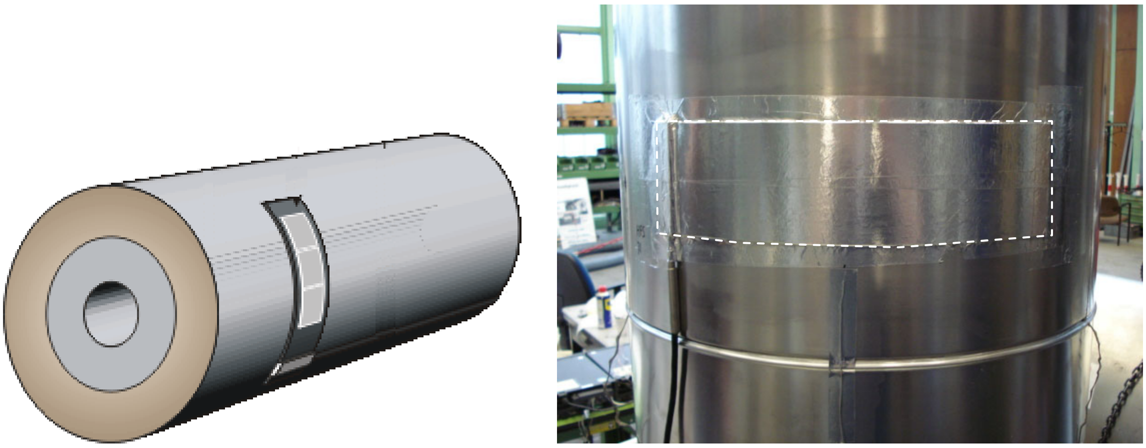
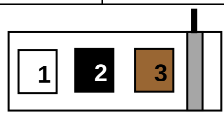


Figure 3. (a) HFT mounted on the pipe line. (b) The HFT (contours dotted line) can barely be seen as it is covered with an aluminum layer to match the emittance of the outer aluminum jacket of the pipe.

Table 1. Heat Flux Transducer (HFT) specifications (TNO)

Item	Description
Heat flux measurement	3 separate heat flux sensors
Temperature measurement	4 type K thermocouples
Flexibility	30 mm minimum radius
Sensitivity (nominal) at 20 °C	50 μV/Wm^{-2}
Expected accuracy (to 50 °C)	within 2.5 %
Temperature coefficient of the sensitivity	–0.17 %/°C
Temperature range	0-100 °C
Pressure range	1-110 bara (watertight)
Cover dimensions	140x 360 mm
Thickness	1.2 mm
Conductivity	Ca 0.2 W/(m·K)
Thermal conductance	Ca 0.2W/(m·K) / 1.2mm = 167W/(m^{2}K)
Time constant $\tau_{63\%}$	Ca 5 s

Table 2. Calibration values of Heat Flux transducer HFT1 and HFT2

Name	HFT1	HFT2
Heat Flux Sensor Type	Belt form	Belt form
Serial Number	0071	0072
Calibration Value @ 20 °C Sensor 1 Sensor 2 Sensor 3	 21.6 $W/m^2/mV$ 21.4 $W/m^2/mV$ 21.1 $W/m^2/mV$	 22.2 $W/m^2/mV$ 22.6 $W/m^2/mV$ 22.1 $W/m^2/mV$
Inaccuracy of Calibration Value	2.5 %	2.5 %
Temperature Correction Calibration Value	0.17 %/°C	0.17 %/°C
Electrical Resistance Sensor 1 Sensor 2 Sensor 3	 2.0 kΩ 2.0 kΩ 2.0 kΩ	 2.0 kΩ 2.0 kΩ 2.0 kΩ
Maximum Temperature	100 °C	100 °C
Maximum Pressure	100 bar	100 bar
Position		

HEAT FLUX TRANSDUCERS CALIBRATION

Calibration values of the HFT's used in the test can be found in Table 2. The Heat Flux Transducers are calibrated in the 'absolute calibration apparatus' [8]. A hot and cold plate create an heat flux through the filling material, see Figure 4. An electrical heating element is located in the hot plate. If the temperature of the heating element is equal to the temperature of the hot plate, all heat will flow upwards (through the filling material). This is controlled by an heat flux sensor between the hot plate and the electrical heater, the so-called zero-indicator.

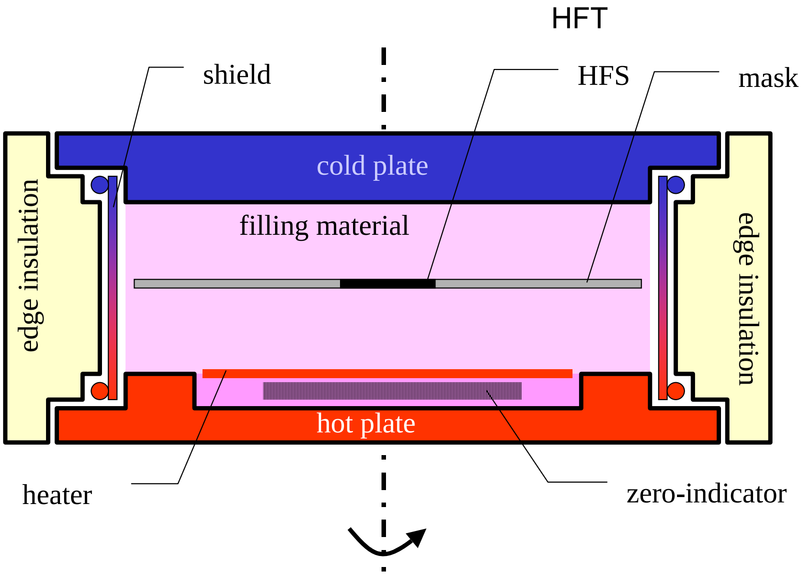


Figure 4. HFT absolute calibration apparatus

In this set-up all the dissipated electrical energy causes a homogeneous heat flux through the filling material. The heat flux can be calculated from the known electrical energy dissipation and the area of the heating element.

Heat losses at the edge of the set-up are eliminated by using a highly conductive metal shield. This metal shield is mounted around the filling material as a cylinder. At the upper and lower side of the shield is supplied by water channels which control respectively the cold and hot temperature. In this way a linear temperature gradient across the shield is created. This temperature gradient is equal to the gradient in the filling material. In addition the edge of the apparatus is provided by insulation.

The to be calibrated Heat Flux Transducer is located in the middle of the filling material and is surrounded by a mask with the same thermal properties and thickness.

The performance of the calibration at TNO is according to ASTM C1130 (1995). The calibration apparatus of TNO meets the requirements of the International Standards ASTM C177, DIN 52612 and ISO 8302. The TNO Calibration Apparatus has a few deviations from the common International Standards. These deviations have a positive effect on the result of the calibration.

- The heat losses through the edge are almost completely eliminated by the thermal shield.
- The 'zero-indicator' consists of thousands of thermocouples. So the sensitiviy of the control parameter to equalize the temperature of the heater and the hot plate is very high.

INSULATION VALUE OF PIPES

Standardized material test methods are employed to determine the thermal conductivity of insulation materials as function of temperature, where only a small temperature difference over the specimen is used. However in reality a large temperature difference may exist over the insulation material. The effective thermal conductivity for such a system, also called apparent thermal conductivity or k-value, now involves the heat conductivity over a large temperature range. The performance of the total thermal insulation system as it is actually put to use is defined as the overall k-value for actual field installation. The overall k-value may deviate significantly from the apparent thermal conductivity.

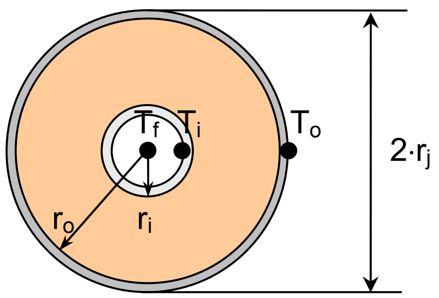


Figure 5. Heat flow through cylindrical surfaces

The steady state heat per unit area of outer surface of insulation flux ‘q’ [W/m^2] as measured by the HFT divided by the temperature difference over the pipe, is a measure for the insulating value of the pipe, also referred to as the conductance ‘C’ [W/(m^{2}K))], see Figure 5:

$$C = \frac{q}{\left(T_o - T_i\right)} = \frac{1}{R} \tag{1}$$

where ‘T_o’ is the outer insulation surface temperature, ‘T_i’ the inner insulation surface temperature, ‘r_o’ is outer insulation surface radius and ‘r_i’ is inner insulation surface radius. The reciprocal of the conductance ‘C’ is the areal thermal resistance ‘R’ [(m^{2}K)/W] of the pipe, defined per unit area of outer surface of insulation.

The overall thermal conductivity ‘λ_o’ [W/(m·K)] of the pipe insulation is defined as:

$$\lambda_o = \frac{q \cdot r_j \cdot \ln\left(\frac{r_o}{r_i}\right)}{\left(T_i - T_o\right)} = C \cdot r_j \cdot \ln\left(\frac{r_o}{r_i}\right) \tag{2}$$

As discussed before, the thus defined insulation value is not necessarily a unique material property, but rather depend on how the material is applied, material stacks used, the dimension of the specimen, and by the specific hot-side and cold-side temperatures.

LNG TEST PIPES

Three pieces of LNG pipes where procured, see Figure 1:

Pipe 1 ‘PI’: A two layer Polyisocyanurate insulated pipe with aluminum jacket,

Pipe 2 ‘PU’: A two layer Polyurethane insulated pipes with aluminum jacket,

Pipe 3 ‘VI’: Vacuum Insulated pipe.

Dimensions and properties of the pipes are given in Figure 6 and Table 3. The bottom end of the pipes is insulated to minimize thermal end effects. With regard to the applied insulation, the pipes where measured “as is”. Prior to testing, the outer aluminum jacket was temporarily removed to locate the position of underlying isolation joints, see Figure 6.

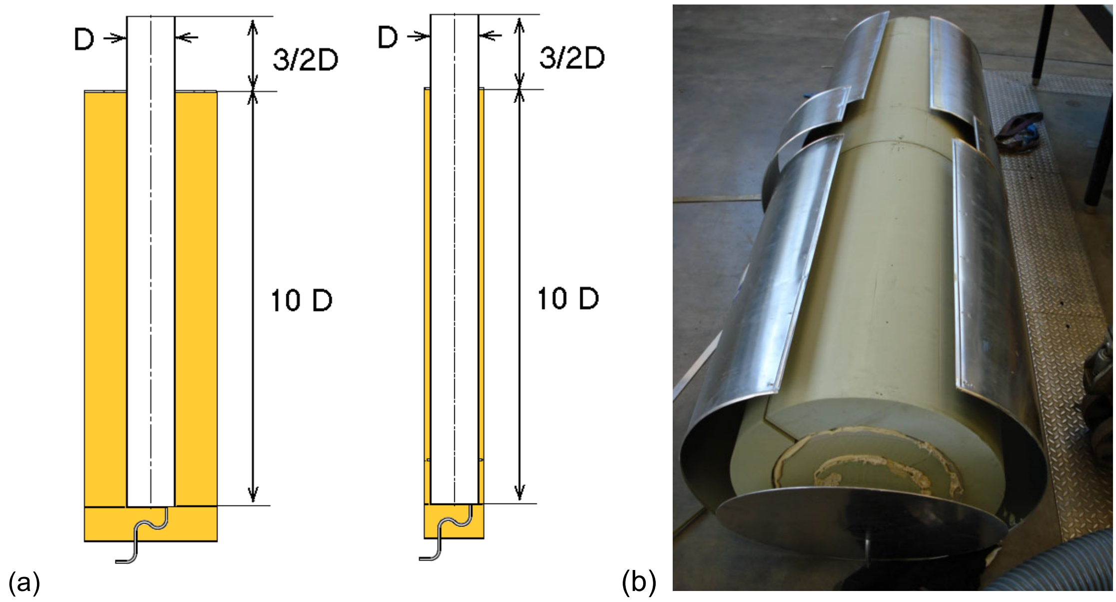


Figure 6. (a) Test pipe dimensions conventional PI & PU insulated pipes and VI pipe (b) PI Insulated pipe with outer aluminum jacket temporarily removed to locate insulation joints prior to thermal testing.

Table 3. Specification LNG test pipes

Pipe data	PI (Pipe1)	PU (Pipe2)	VI (Pipe3)
Inner pipe, outer diameter 'D=2·r_i'	219.1 mm	219.1 mm	219.1 mm
Inner pipe, wall thickness	2.77 mm	2.77 mm	3.76 mm
Outer insulation diameter '=2·r_o'	567 mm	570 mm	267 mm
Outer pipe wall thickness	n.a.	n.a.	3.05 mm
Outer jacket dia '=2·r_j'	568mm	571mm	273mm
Thickness aluminium jacket	0.6 mm	0.6 mm	n.a.
Insulation thickness	174 mm	176 mm	24.1 mm
Factor eqn (2) $r_j \cdot \ln(r_o / r_i)$	0.270 m	0.273 m	0.0270 m
Insulation type	2 layers of preformed shells, 170 mm thick, glued, with slip planes in-between layers and pipe.		Ca 20 radiation shields with molecular sieves, $\approx 10^{-4}$ mbar (cold)
Insulation density	ρ=50 kg/m^3	ρ=60kg/m^3	
Intrinsic thermal conductivity insulation material 'λ_i' @ ambient	$\lambda_i \approx$26mW/(m·K) estimated from ρ	λ_i=24 mW/(m·K)	
Pipe length	11.5D		
Insulated length pipe	10D		
Design pressure	20 barg		
Design temperature	-196 ^{o}C to +80 ^{o}C (liquid nitrogen cool down)		
Pipe material	AISI 304L		

MEASUREMENTS

The measurements are conducted according to ASTM C 1041 – 85 (2007) Standard Practice for "In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers" [6].

The pipes where erected vertically in an open hall, see Figure 7 and Figure 8. K-type thermocouples where placed on the pipe surface, which were used to check the extent of pipe end effects. The thermocouples where taped to the surface such that at least 100 mm of the thermocouple is in contact with the surface. The emittance of the tape is matched with that of the jacket surface.

The HFT is placed on the outer surface of the pipe, using thermal paste to minimize any contact resistance. The emittance of the HFT is matched with the emittance of the aluminum jacketing, by applying a 0.04 mm thin layer of adhesive aluminum tape to the HFT. The HFT is mounted away from insulation joints and away from thermal pipe end effects. For the PI and PU pipes thermal end effects where not found present anymore circa one outer pipe diameter from the ends, see Figure 7. For the VI pipe thermal end effects were more pronounced, and were not found circa 3 outer pipe diameters from the ends. In one specific case a second HFT was mounted deliberately onto an insulation joint.

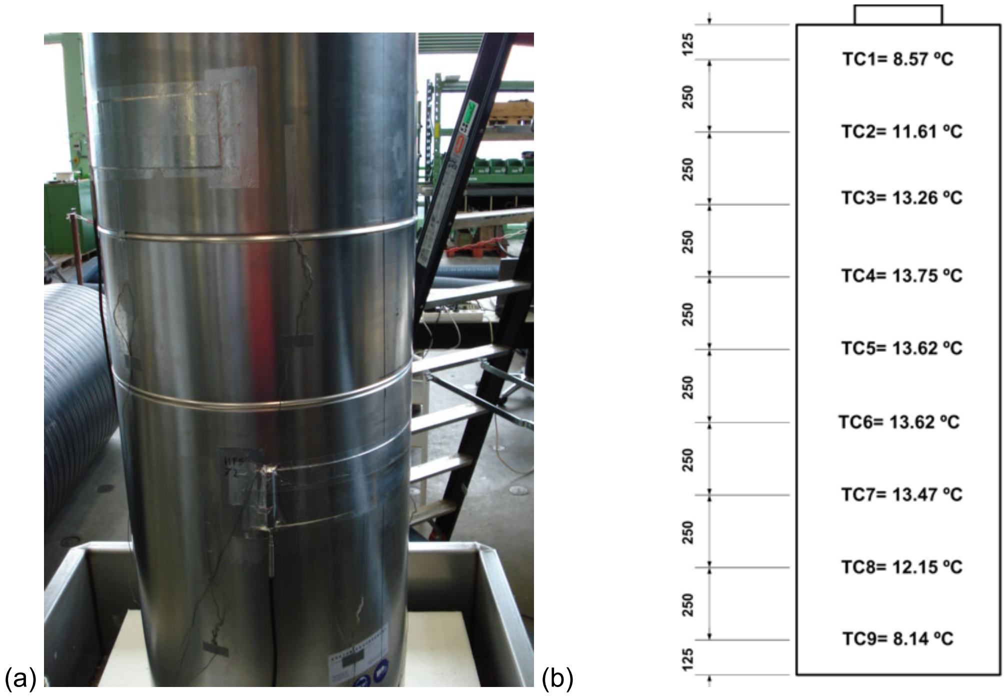


Figure 7. (a) PI pipe erected vertically with the upper HFT1 mounted away from insulation joints and HFT2 mounted deliberately onto an insulation joint. Shield removed. (b) Assessment of thermal end effects. Jacket temperatures at certain instant in time, of PI pipe filled with N_2 in pseudo steady state. Shield removed.

Figure 8. VI pipe erected vertically with HFT mounted. Shield removed.

The pipes where filled with liquid nitrogen. The N_2 filling level of the pipe was set to >10D, using automatic level control. The operating pressure during the test was 1 atm. The data of the thermocouples and HFT is recorded each 30 s with a Fluke Netdaq 2640A in slow scan mode. The data was recorded until a pseudo steady state is obtained. At that point in time the heat flux is used to derive the insulation value of the pipe. The criterion for pseudo steady state condition is that the average HFT reading over two consecutive 5-min periods does not differ by more than 2% [6]. The duration of the test, from initial filling of the pipes to the pseudo steady state is approximately 1 day.

Tests are performed with a polyethylene shield around the pipe, to damp out outside climate variations. The shield consisted of a 2.25m long pipe, diameter 800 mm. The ambient temperature outside the polyethylene shield is recorded ('Tamb-1'). Also the temperature between the pipe and the shield is recorded ('Tamb-2').

The heat fluxes are corrected for the temperature coefficient of calibration of the HFT. For the inner pipe temperature the boiling point of liquid N_2 is used -195.9 ^oC.

Insulation performance degradation in time, i.e. by moisture penetration, is not investigated.

RESULTS

Figure 9 to Figure 11 show the measured heat fluxes and temperatures in time for PI pipe and VI pipe, just after filling the pipes with N_2,. At startup the pipes are not necessarily in thermal equilibrium with the surrounding (non-zero initial heat fluxes). The data shown are averages over consecutive 5 min periods. Graphs of the PU pipe are similar to the graphs of the PI pipe and are not shown. After the pseudo steady state is achieved the conductance's 'C' [mW/(m^2K)] and overall thermal conductivities are determined, see Table 4 to Table 6.

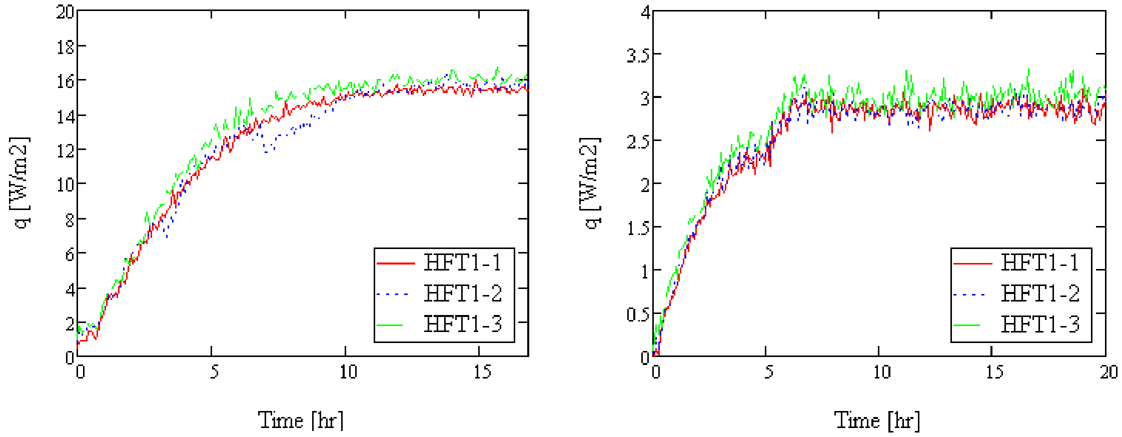


Figure 9. Heat flux 'q' averaged over consecutive blocks of 5 minutes.
(a) PI pipe (b) VI pipe

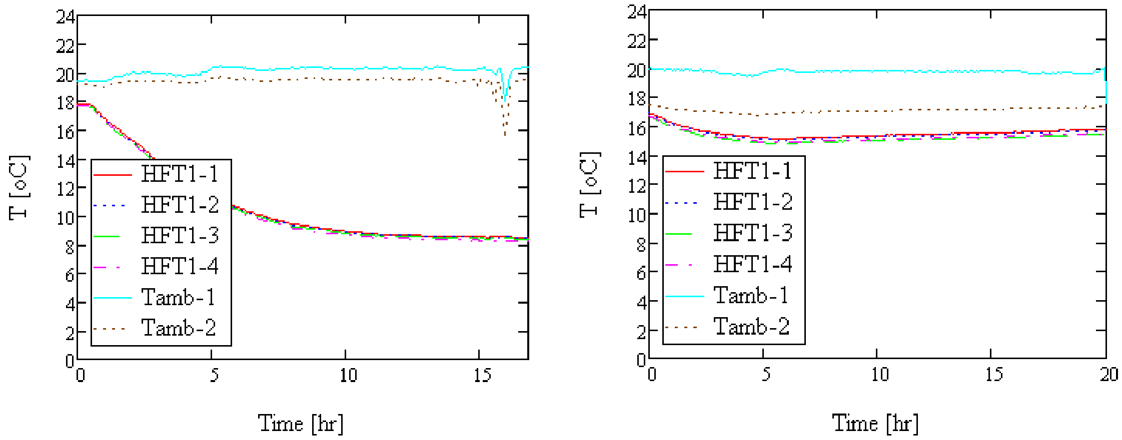


Figure 10. Temperatures averaged over consecutive blocks of 5 minutes.
(a) PI pipe (b) VI pipe

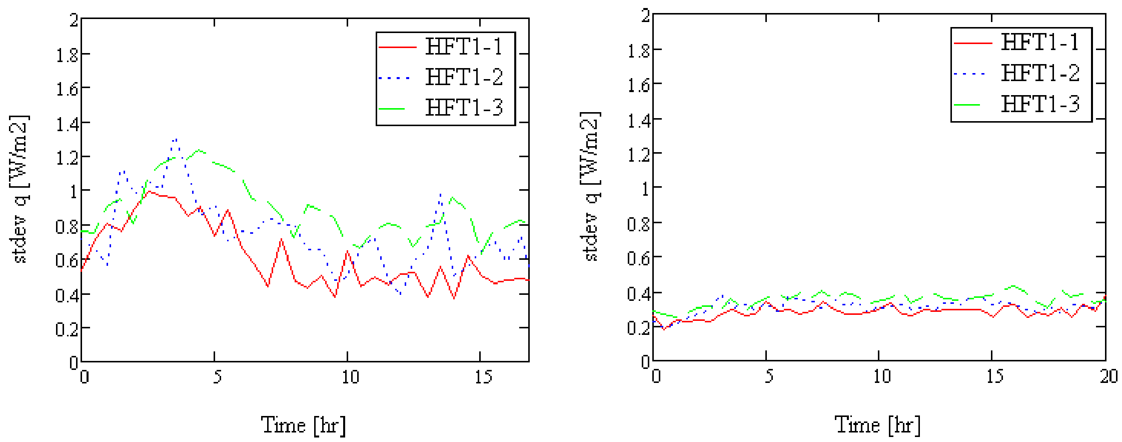


Figure 11. Standard deviation heat flux 'σ_q' over consecutive blocks of 30 minutes.
(a) PI pipe (b) VI pipe

Table 4. Measured pseudo steady state conductance ‘C’ and standard deviation, for the PI pipe, PU pipe and VI pipe (based on outer surface).

	PI	PU	VI
	[mW/(m^{2}K)]	[mW/(m^{2}K)]	[mW/(m^{2}K)]
HFT1-1	74.0±4.0%	69.2±4.5%	13.5±9.1%
HFT1-2	74.5±3.6%	67.5±4.6%	13.4±10.8%
HFT1-3	77.4±5.4%	71.2±5.2%	13.7±10.5%

Table 5. Measured overall thermal conductivity ‘λ_o’ and standard deviation, for the PI pipe, PU pipe and VI pipe.

	PI	PU	VI
	[mW/(m·K)]	[mW/(m·K)]	[mW/(m·K)]
HFT1-1	20.0±4.0%	18.9±4.5%	3.76±9.1%
HFT1-2	20.2±3.6%	18.5±4.6%	3.73±10.8%
HFT1-3	21.0±5.4%	19.5±5.2%	3.81±10.5%

Table 6. Heat loss per meter pipe and standard deviation, for the PI pipe, PU pipe and VI pipe. Boundary temperatures of 300 K and 77 K.

	PI	PU	VI
	[W/m]	[W/m]	[W/m]
HFT1-1	29.5±4.0%	27.7±4.5%	2.59±9.1%
HFT1-2	29.7±3.6%	27.0±4.6%	2.57±10.8%
HFT1-3	30.8±5.4%	28.5±5.2%	2.62±10.5%

The measured overall thermal conductivity for i.e. PU is lower than the intrinsic thermal conductivity of PU at room temperature, Table 3. This has to do with the drop in thermal conductivity of foam at cryogenic temperatures. Part of the insulation near the pipe is at cryogenic temperatures. A typical example of the drop in heat conductivity of PU foam (64kg/m^3 PU) is reported in [7], which gives the intrinsic thermal conductivity as function of temperature. The heat conductivity drops from circa 26 mW/(m·K) at room temperature to circa 9.2 mW/(m·K) at 77K. The temperature averaged heat conductivity over the temperature range -195.9 ^{o}C to 8 ^{o}C gives an apparent heat conductivity of circa 19.2 mW/(m·K) which compares well with the measured overall thermal conductivity as given in Table 5 of circa 19 mW/(m·K).

In case of the PI pipe, a second HFT was mounted deliberately onto insulation joint, yielding a circa 1.5% higher conductance value than away from the joint.

ACCURACY

The overall accuracy of the measured insulation conductance ‘C’ and the overall thermal conductivity ‘λ_o’ consists of systematic errors and dynamic errors. The dynamic error dominates.

Systematic errors

Table 7 gives a compilation of systematic error sources, where the total error is obtained by simple addition of each individual error source (worst case assumption). No use is made of the assumption that the errors are normal distributed and independent, in which case quadratic addition is allowed and a less conservative value is obtained.

Using expression (1) and (2) the relative measurement accuracy of the insulation conductance ‘C’ and overall thermal conductivity ‘λ_o’ can be written as a summation of separate contributions:

$$\frac{\Delta C}{C} = \left(\frac{\partial C}{\partial a}\right)\cdot\frac{\Delta a}{C} + \left(\frac{\partial C}{\partial V}\right)\cdot\frac{\Delta V}{C} + \left(\frac{\partial C}{\partial T_o}\right)\cdot\frac{\Delta T_o}{C} + \left(\frac{\partial C}{\partial T_o}\right)\cdot\frac{\Delta T_i}{C} = \frac{\Delta a}{a} + \frac{\Delta V}{V} - \frac{\Delta T_o}{T_o - T_i} + \frac{\Delta T_i}{T_o - T_i} \quad (3)$$

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta C}{C} + \frac{\Delta r_j}{r_j} + \left(\frac{\Delta r_o}{r_o} - \frac{\Delta r_i}{r_i}\right)\cdot\frac{1}{\ln(r_o/r_i)} \quad (4)$$

where the heat flux ‘q’ of the HFT in expression (1) is written as the HFT voltage ‘V’ output signal times the calibration value ‘a’ of the HFT.

The short time error of the Fluke Netdaq 2640A voltage measurement in the 90mW range is 0.01% and negligible. The accuracy of the K-type thermocouple measurement in slow scan mode is ±0.4^{o}C. Combined with a large temperature difference over the pipe (≈200^{o}C) this gives an error of circa ±0.2%.

Next to the errors defined above, the HFT adds a small thermal resistance to the pipe. The relative error in insulation conductance due to this effect can be approximated by ‘C/(C+c)’. In this expression ‘C’ is the measured pipe insulation conductance and ‘c’ denotes the HFT conductance. Practical values for PI and PU pipe is C≈0.07W/(m^{2}K) and for the HFT c≈170W/(m^{2}K) (≈0.2W/(m·K)/1.2mm). This results in a relative error of less than 0.1%. For a VI pipe the associated relative error is even smaller.

Table 7 Systematic error in determination of the insulation conductance and overall thermal conductivity of the pipe.

ID	Systematic error conductance ‘C’ ±	Systematic error overall thermal conductivity ‘λ_o’ ±
Added thermal resistance pipe by HFT	±0.1%	±0.1%
Voltage HFT	±0.01%	±0.01%
Temperature	±0.2%	±0.2%
Inner pipe dimension	n.a.	±0.15%
Outer pipe dimension	n.a.	±0.1%
HFT calibration value	±2.5%	±2.5%
Total added (worst case)	±2.8%	±3.1%

Dynamic errors

The dynamic errors associated with the stability of the heat flux signals in time, as mentioned in Table 4 to Table 6 (circa ±5% for PI and PU, and circa ±10% for VI), are larger than the systematic error involved (circa ±3%).

CONCLUSION

In this paper a large-area heat flux and temperature sensor (HFT) is used for the evaluation of the insulation value of cryogenic pipes. The HFT is flexible and clamp-on. The test method is relatively simple and can be used in-situ. The HFT makes it possible to monitor insulation performance over elongated times and to study localized effects (thermal bridges). The method complies with the Standard Practice ASTM C 1041 – 85 (2007). The HFT is originally designed for subsea oil pipelines, is completely water-tight and can withstand hydrostatic pressures up to 110 bar.

Three commercial 8 inch rigid cryogenic pipes are measured, with polyisocyanurate (PI), polyurethane (PU) and vacuum insulation (VI). The measured heat loss and dynamic error per meter pipe is given by circa 27.7 and 30±5% W/m for the PI respectively PU insulated pipe and 2.6±10% W/m for the VI insulated pipe. The systematic error is circa ±3%, of which the HFT calibration error contribution is ±2.5%. The measured overall thermal conductivity for i.e. PU insulated pipe is lower than the intrinsic thermal conductivity of PU at room temperature. This is consistent with the fact that the thermal conductivity drops at cryogenic temperatures. The measured overall thermal conductivity of circa 19 mW/(m·K) compares well with the apparent thermal conductivity of circa 19.2 mW/(m·K), derived from the intrinsic thermal conductivity as function of temperature of PU foam as given in literature.

Recently, the test method is also used to measure the overall insulation value of flexible cryogenic pipes, consisting of a multilayer of fabrics, plastic sheets and SS coil.

REFERENCES CITED

[1] ASTM C335 “Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulation”

[2] ASTM C1033 “Test Method for Steady-State Heat Transfer Proper ties of Pipe Insulation Installed Vertically”

[3] EN ISO 8497:1997 “Thermal insulation. Determination of steady-state thermal transmission properties of thermal insulation for circular pipes”

[4] “Cryogenic Thermal Insulation Systems”, James E. Fesmire, Stan D. Augustynowicz, 16thThermal and Fluids Analysis Workshop Orlando, Florida, August 9, 2005, Cryogenics Test Laboratory, NASA Kennedy Space Center

[5] ATM C 1041 – 85 (Reapproved 2007) “Standard Practice for In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers”

[6] “A Direct Measurement System to obtain the Thermal Conductivity of Pipeline Insulation Coating Systems under Simulated Service Conditions”, D. Haldane, Heriot-Watt University; F. van der Graaf, A. M. Lankhorst, TNO Institute of Applied Physics, Offshore Technology Conference, 3 May-6 May 1999, Houston, Texas

[7] “Low Temperature Properties of Expanded Polyurethane and Polystyrene”, L. L. Sparks, in STP718 Thermal insulation performance: symposium, editors D. L. McElroy, Ronald Phillip Tye, ASTM Committee C-16 on Thermal and Cryogenic Insulating Materials, Published 1980, pg 446.

[8] “Research in Calibration and Application Errors of Heat Flux Sensors”, Graaf, F. van der, published in Building Applications of Heat Flux Transducers, ASTM STP 885, edited by E. Bales, M. Bomberg and G.E. Courville, ASTM, 1985.