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Influence of tube wall longitudinal heat conduction on temperature measurement of cryogenic gas with low mass flow rates

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ABSTRACT

Longitudinal heat conduction is an important parameter in the cryogenic field, especially in cryogenic heat exchangers. In the present study, the parasitic effect of tube wall longitudinal heat conduction on temperature measurement within the tube has been studied for cryogenic gas with low mass flow rates by finite element method and experimental tests. The effects of various parameters such as tube outlet temperature, tube wall thermal conductivity, mass flow rate, and tube wall thickness have been investigated. Axial positioning errors of temperature sensor due to tube wall longitudinal heat conduction were higher for lower gas flow rates. The results showed that the tube wall thermal conductivity leads to axial heat conduction within the tube wall, but the higher tube wall thermal conductivity does not lead to bigger axial positioning error of temperature sensor at tube outlet. According to data obtained from simulations and experiments, sensor with distance of 5 mm from tube outlet had 14.92% and 8.51% temperature measurement error (with respect to gas flow temperature at tube outlet) for tube wall thermal conductivities of 16 and 400 W m^{-1} K^{-1}, respectively.

1. Introduction

Heat transfer and its associated problems are the main subjects of cryogenic applications. All the cryogenic processes operate at very low temperatures. Conventional design theory usually fails in cryogenic applications and needs modification with considering various parameters such as tube wall longitudinal heat conduction through the wall material, and heat in-leak from the surrounding. The effect of tube wall longitudinal heat conduction has been studied by many researchers. This phenomenon appears when two axial distinct points of tube have temperatures with large difference. This situation exists in cryogenic heat exchangers and equipment operating in cryogenic applications. Heat exchangers are the main equipment in cryogenic applications and their performance can be evaluated by measuring cold and hot fluids temperatures. Therefore, measuring temperatures is an important field in cryogenic applications. Pacio and Dorao [1] reviewed the thermal hydraulic models of cryogenic heat exchangers. They introduced physical effects such as changes in fluid properties, flow maldistribution, axial longitudinal heat conduction, and heat leakage as the main challenges of cryogenic heat exchangers. Aminuddin and Zubair [2] studied the various losses in a cryogenic counter flow heat exchanger numerically. They discussed the effect of longitudinal heat conduction loss as a parasitic heat loss by conduction from heat exchanger cold end to the

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Nomenclature

T_g	gas temperature (K)	c_g	gas specific heat (J T^{-1} kg^{-1})
T_w	tube wall temperature (K)	Q	heat flux (W m^{-2})
T_{amb}	ambient temperature (K)	A_w	tube wall cross section area (m^2)
D	inner diameter of tube (m)	k	tube wall thermal conductivity (W m^{-1} K^{-1})
m_g	gas mass flow rate (kg s^{-1})	Re	Reynolds number, dimensionless
h_g	convection heat transfer coefficient (W m^{-2} K^{-1})		

adjacent components, but they did not perform any experimental tests. Krishna et al. [3] studied the effect of longitudinal heat conduction in the separating walls on the performance of three-fluid cryogenic heat exchanger with three thermal communications. They reasoned that the thermal performance of heat exchangers operating at cryogenic temperature is strongly governed by various losses such as longitudinal heat conduction through the wall, heat in-leak from the surroundings, and flow maldistribution. Gupta et al. [4] investigated the second law analysis of counter flow cryogenic heat exchangers in presence of ambient heat in-leak and longitudinal heat conduction through wall. They cited the importance of considering the effect of longitudinal heat conduction in the design of cryogenic heat exchangers. Nellis [5] presented a numerical model of heat exchanger in which the effect of axial conduction, property variations, and parasitic heat losses to the environment have been explicitly modeled. He concluded that small degradation exists in the performance of heat exchanger at conditions which the temperature of heat exchanger cold end is equal to temperature of the inlet cold fluid. Narayanan and Venkatarathnam [6] presented a relationship between the effectiveness of a heat exchanger losing heat at the cold end. They studied a Joule–Thomson cryo-cooler and concluded that the hot fluid outlet temperature will be lower in the heat exchangers with heat in-leak at the cold end with respect to heat exchangers with insulated ends. Ranganayakulu et al. [7] studied the effect of longitudinal heat conduction in compact plate fin and tube fin heat exchanger using finite element method. They indicated that the thermal performance deteriorations of cross flow plate-fin, cross flow tube-fin and counter flow plate-fin heat exchangers due to longitudinal heat conduction may become significant, especially when the fluid capacity rate ratio is equal to one and when the longitudinal heat conduction parameter is large. Taler and Duda [8] investigated the conjugated heat transfer in the flowing fluid and tube wall using CFD. They cited that heat conduction in the tube wall has large influence on temperature distribution, especially when the mass flow rate of the fluid is low. Jaremkiewicz et al. [9,10] studied the measurement of transient fluid temperature. They showed the differences between the true temperature and the measured temperature of fluid due to time required for the transfer of heat to the thermocouple placed inside a heavy thermometer pocket. Cebula [11] investigated the influence of axial heat conduction in a thermometer on the temperature measurement error, but the influence of axial heat conduction through tube wall was not within the scope of his work. As can be seen, the influence of tube wall longitudinal heat conduction on temperature measurement of cryogenic gas flow was not studied by any researcher.

Evaluating the effectiveness of cryogenic heat exchangers is very important. The effectiveness factor is calculated by the gas flow temperatures at tube inlet and outlet. The inlet and outlet temperatures of fluids may be different from values measured by sensors. This event takes place when the effect of tube wall longitudinal heat conduction is neglected and the sensors are placed in inappropriate axial positions. Therefore, the effectiveness of cryogenic heat exchangers may be evaluated without considering errors associated with axial position of sensors and leads to obtain incorrect values. Although longitudinal heat conduction has a great importance in the cryogenic engineering, but almost all investigations have been focused on the cryogenic heat exchangers. In the present paper, the effect of tube wall longitudinal heat conduction on the gas flow temperature with low mass flow rates and its influence on the temperature measurement have been discussed. Experimental tests and simulations by finite element method were performed to indicate this phenomenon. Several parameters influencing on tube wall longitudinal heat conduction were studied to investigate temperature measurement error associated with axial position of temperature sensor within the tube. This phenomenon has not been investigated by other researchers as yet and the current study could be used to introduce a new predictable source of error in the temperature measurements.

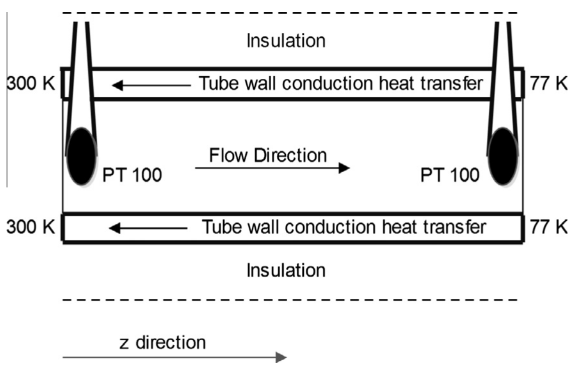

Fig. 1. Scheme of model used for simulating the tube wall longitudinal heat conduction.