Thermal Design Considerations and Performance Evaluation of Cryogenic Tube in Tube Heat Exchangers

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ABSTRACT: *Heat exchangers are the most important equipment in refrigeration processes. Design and modeling of heat exchangers operating at low temperatures are different from other regular heat exchangers. This study includes two sections. In the first section, design and modeling considerations needed for evaluating the real thermal behavior of heat exchangers at low temperatures were discussed. These considerations are usually neglected by researchers who have modeled the heat exchanger at low temperatures. In the second section, a counter current helically coiled tube in tube heat exchanger operating in hydrogen liquefier was modeled and simulated considering notes discussed in the first section. The model was validated compared with the data presented by literature. The results showed the small positive effect of longitudinal heat conduction on hydrogen liquefaction. The heat in-leak into cold fluid resulted in higher cold fluid outlet temperature and higher hot fluid outlet temperature. Simulations showed that the heat in-leak into cold fluid leads to limit the overdesign for cryogenic heat exchangers. A comparison between models with considering different assumptions was presented and showed that the result may vary significantly based on the regarded assumptions.*

EYWORDS: *Heat exchanger; Longitudinal heat conduction; Heat in-leak; Low temperature'; Refrigeration.*

INTRODUCTION

Heat exchangers are the most important equipment in refrigeration processes. The heat exchangers effectiveness has an influence on the efficiency of the whole system [1]. Many studies focused on the design and modeling the cryogenic heat exchangers (heat exchangers operating at low temperatures) [2-6]. Because of high needed effectiveness for heat exchangers operating at low temperatures, the design should take various losses into consideration [1]. A gas liquefier produces no liquid if its effectiveness falls below 85%[7]. The performance of cryogenic heat exchangers is deteriorated by various losses such as longitudinal heat conduction through the wall material, heat in-leak from the surrounding, flow maldistribution, etc. which are not normally considered for evaluating the heat exchangers performance [8, 9]. *Pacio* and *Dorao* [10] 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

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cryogenic heat exchangers. *Aminuddin* and *Zubair* [11] 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 adjacent components, but they did not perform any experimental tests. *Krishna et al.* [12] 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, flow maldistribution, etc. *Gupta et al.* [13] investigated the second law analysis of counter flow cryogenic heat exchangers in presence of ambient heat in-leak and longitudinal heat conduction through the wall. They cited the importance of considering the effect of longitudinal heat conduction in the design of cryogenic heat exchangers. *Nellis* [14] 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 in the conditions in which the temperature of heat exchanger cold end is equal to temperature of the inlet cold fluid. *Narayanan* and *Venkatarathnam* [15] 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.* [9] 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. *Saberimoghaddam* and *Bahri* [16-18] studied the performance of recuperative tube in tube heat exchanger at cryogenic temperatures. They considered various parameters such as heat in leak, longitudinal heat conduction, etc. to evaluate the efficiency of a small cryogenic gas liquefier. *Saghatoleslami et al.* [19] discussed about conversion of ortho hydrogen to para hydrogen in hydrogen liquefaction process but they did not present any discussion about cryogenic heat exchanger effectiveness. *Mehrpooya et al.* [20] also published paper related to optimum pressure distribution in design of cryogenic NGL recovery processes. They did not focus on the effective parameters of cryogenic heat exchanger design.

This study includes two sections. The first section presents a discussion about cryogenic heat exchangers design parameters. These parameters must be considered to design the heat exchangers operating at low temperatures. Researchers neglect considering these parameters despite their importance. These parameters will be introduced and discussed here comprehensively. The comparison will be also presented between cryogenic heat exchanger design and common heat exchanger design. In the second section, a counter current helically coiled tube in tube heat exchanger will be modeled, simulated and analyzed numerically. Also, the performance of this heat exchanger after validation will be analyzed respect to several factors discussed in the first section.

CRYOGENIC HEAT EXCHANGER DESIGN CONSIDERATIONS

Thermal design of cryogenic heat exchanger is different from common heat exchanger design because conventional design theory usually fails in cryogenic applications and needs modification with considering various irreversibilities [7]. In the following, some considerations needed for evaluating the performance of heat exchangers operating at low temperatures will be discussed.

Principles and basic definitions

Despite extensive studies performed in the cryogenic fields, the conventional definition of effectiveness factor is still used for evaluating the performance of heat exchangers operating at low temperatures. The effectiveness of any heat exchanger is defined as the ratio of actual heat transfer to the maximum possible heat transfer as follows [1]:

$$\varepsilon = \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}} \tag{1}$$

Based on the above equation, the effectiveness factor for a heat exchanger can be expressed by equation (2):

$$\varepsilon = \frac{\left(mc_p \Delta T\right)_{\text{cold or hot}}}{\left(mc_p\right)_{min} \times \left(T_{hot-in} - T_{cold-in}\right)} \quad (2)$$

If the cold stream of the heat exchanger is a fluid with the least heat capacity, then the effectiveness factor can be expressed as follows:

$$\varepsilon = \frac{\left(\Delta T\right)_{cold}}{\left(T_{hot-in} - T_{cold-in}\right)} = \frac{\left(T_{hot-in} - T_{cold-in}\right) - \delta}{\left(T_{hot-in} - T_{cold-in}\right)} \quad (3)$$

Where δ is temperature approach as follows:

$$\delta = \left(T_{hot-in} - T_{cold-in}\right) - \left(\Delta T\right)_{cold} = \left(T_{hot-in} - T_{cold-in}\right) - \left(T_{cold-out} - T_{cold-in}\right) \quad (4)$$

So:

$$\delta = \left(T_{hot-in} - T_{cold-out}\right) = \text{Temperature Approach} \quad (5)$$

By defining θ as $\left(T_{hot-in} - T_{cold-in}\right)$ the effectiveness factor can be expressed as follows:

$$\varepsilon = \frac{\theta - \delta}{\theta} \quad (6)$$

As can be seen, the effectiveness factor could be calculated by θ and δ. This means that the effects of internal conditions of the heat exchanger and external heat flux into streams can be only considered when these parameters affect the inlet and outlet fluids temperatures. Temperature approach usually takes place at the hot end of the counter current tube in tube heat exchangers. The lower temperature approaches result in higher effectiveness factors. According to heat transfer principles, the temperature approach cannot take negative values. Therefore, the effectiveness factor can take maximum value of 1 for the common heat exchanger working in normal conditions. *Gupta* and *Atrey* [1] used degradation factor to show the influence of heat in-leak and longitudinal heat conduction in the counter current cryogenic heat exchangers as follows:

$$\tau = \frac{\varepsilon_{NC,NHL} - \varepsilon_{WC,WHL}}{\varepsilon_{NC,NHL}} \quad (7)$$

Where NC= no conduction, WC= with conduction, NHL= no heat in-leak and WHL= with heat in a leak. Based on the study performed by the authors, it could be seen from Equation (7) that τ is 0 if no losses are considered in the calculations of ε. The value of τ increases with considering losses in calculations. On the other hand, calculation associated with actual heat transfer is not easily possible for a cryogenic heat exchanger with heat in-leak and wall longitudinal heat conduction. Fig. 1 shows the influence of heat in-leak on the temperature profiles of cold and hot streams. As can be seen, if the cold fluid flows in annular section and the hot fluid flows in inner tube, temperature cross can take place in the counter current heat exchanger with heat in-leak into cold fluid. The temperature cross results in negative δ at the hot end of the heat exchanger and accordingly, the value of ε will be higher than 1 according to equation (6). Also, the value of $\varepsilon_{WC,WHL}$ in Equation (7) will be higher than $\varepsilon_{NC,NHL}$ and the definition of τ will not suitable in this situation. So, using degradation factor is not recommended for cryogenic heat exchanger with a cold stream exposing to heat in-leak. This factor was not used in the current study.

On the other hand, transferring energy into hot fluid reduces the value of heat in-leak because of decrease in temperature difference between fluid and surrounding, but the hot fluid usually flows through the inner tube and is not exposed to heat in-leak. Usually, the cold fluids have lower pressures respect to hot fluids in cryogenic liquefaction applications, because the cold fluids are formed after expansion valve. The low pressure cold fluids have the role of refrigerant returning from the end of processes. It is better to flow low pressure fluids through annular section to avoid mechanical failure of heat exchangers. Consequently, although using degradation factor has no conceptual problem, but applying external heat transfer into hot fluid cannot be a suitable assumption for some cryogenic heat exchangers.

Heat capacity ratio

The heat capacity ratio is usually used for analyzing the performance of cryogenic heat exchangers. It is common to use this factor as an independent variable. The value of degradation factor vary versus the change of heat capacity ratio and this event has been used by some researchers [1]. This parameter is different for any type of

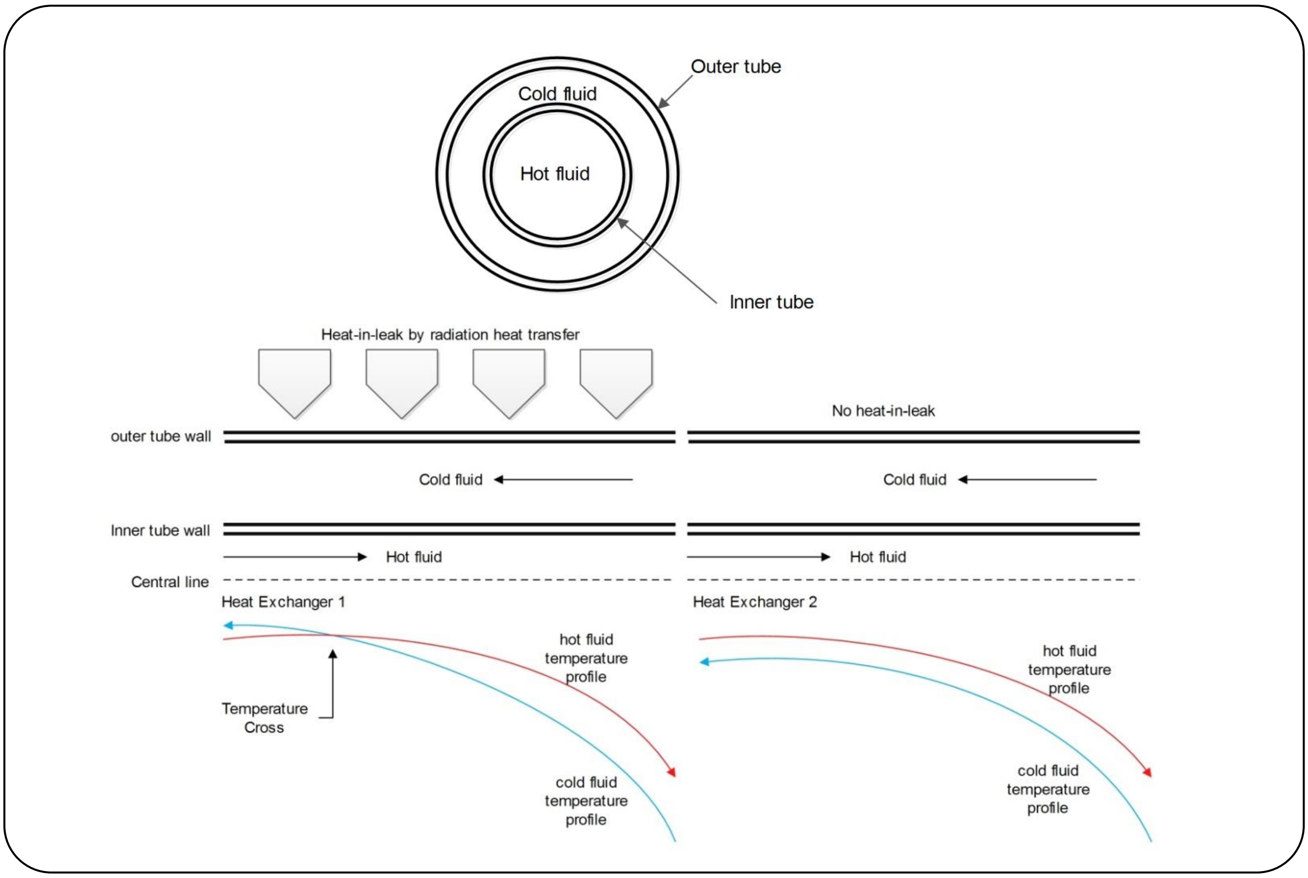

Fig. 1: Temperature profiles for hot and cold streams in a counter current tube in a tube heat exchanger with and without radiation heat-in-leak.

cryogenic plants [7]. Moreover, this ratio is not constant at temperatures near the critical point for permanent gases such as hydrogen. Therefore, this factor must be used carefully to avoid getting unreal results. High performance heat exchangers are critical components in many cryogenic systems. The cryogenic heat exchangers must have sufficiently high efficiency [4]. So, all considerations must be regarded to design proper heat exchangers. The Heat capacity of some gases like hydrogen varies erratically near the critical point and the final heat exchangers in liquefaction units operate near the critical point. Fig. 2 shows the variation of heat capacity ratio versus the temperature in final heat exchanger operating in hydrogen liquefaction unit. As can be seen, this parameter varies from 1.1 to 1.6 along with the heat exchanger for equal mass flow rates. In addition, mass flow rates for two streams are not equal in the heat exchangers operating in the liquefaction units because high pressure gas liquefies at the end of process partially and liquefied gas is separated from backward stream. Therefore, the values of heat capacity ratio can be higher than those for equal mass flow rates. Heat capacity ratio has been used to analyze the cryogenic heat exchanger performance by several researchers [1, 11]. Some authors [1, 7, 16] have discussed on the heat exchanger thermal behavior for heat capacity ratio of 1 while this condition cannot take place in some cryogenic heat exchangers according to curves shown in Fig. 2. Moreover, the values of heat capacity ratio are not constant along the cryogenic heat exchangers despite using constant values for parametric studies by researchers. Consequently, according to above discussions, parametric study and use of constant heat capacity ratio are not suggested to investigate the performance of cryogenic heat exchanger operating near the gas critical point. In the current study, the actual values of heat capacity were used along the heat exchanger and the values of heat capacity ratio vary along the heat exchanger tubes.

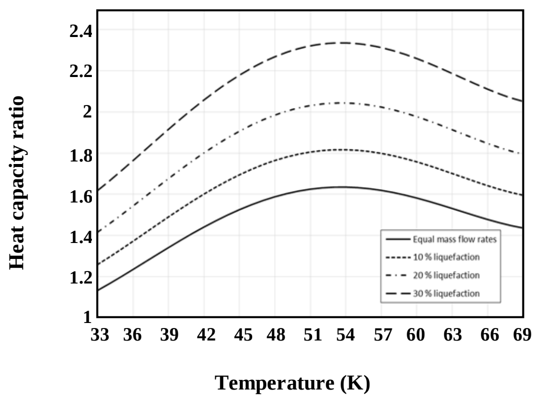

Fig. 2: Variations of heat capacity ratio for final heat exchanger operating in hydrogen liquefaction unit.

Evaluating the size of the heat exchanger

A tube in a tube heat exchanger with given length evaluated by common thermal heat exchanger design has a certain temperature approach at the hot end. If the length of the heat exchanger increases, the temperature approach will decrease while no heat in-leak exists. Decreasing the temperature approach results in a higher effectiveness factor according to equation (6). If external heat flux like radiation heat in-leak is exerted on the heat exchanger, the thermal behavior of heat exchanger will be different. Since the cold fluid has commonly lower pressure in cryogenic applications, it flows through annular section of tube in tube heat exchanger and accordingly, the cold fluid is exposed to radiation heat in-leak. The heat in-leak leads to a temperature increase of cold fluid at heat exchanger hot end compared with no heat in-leak conditions. Actually, the heat in-leak results in reduction in the temperature difference between hot fluid inlet and cold fluid outlet. To design a cryogenic heat exchanger with heat in-leak into cold fluid, determining the accurate length of tubes considering the temperature cross is essential. As a result, considering the longer length for common heat exchanger is not an important design parameter (it is important from economical point of view) and leads to higher effectiveness, but the longer length for a cryogenic heat exchanger may result in a negative effect on heat exchanger performance.

Considerations used in the current study

The advantages of the simulation performed here respect to other studies are as follows:

- Modeling and simulation were done by direct use of actual values of fluid properties.
- Heat in-leak, fluid properties variations versus temperature, and longitudinal heat conduction through separating wall were considered simultaneously.
- The radiation heat transfer formulation was used for simulating the heat in-leak into the cold fluid as an actual condition taking place in cryogenic applications.
- Proper length of cryogenic tube in the tube heat exchanger was chosen to avoid temperature cross caused by heat in-leak.

MODELING PROCEDURE

In accordance with the discussion presented in the previous section, the parametric study of the cryogenic heat exchanger was not performed here. The model was solved by direct use of heat capacities, radiation heat transfer into cold fluid flowing in annular section, and longitudinal heat conduction through separating wall. The energy equations were established in three sections (hot fluid, cold fluid, and separating wall) as follows:

$$A_1 \frac{dT_{cold}}{dz} = Q_\iota + h_{cold}\left(T_{wall} - T_{cold}\right) \tag{8}$$

$$A_1 = \frac{m_{cold} Cp_{cold}}{\pi D}$$

$$A_2 \frac{dT_{wall}}{dz^2} = h_{cold}\left(T_{wall} - T_{cold}\right) - h_{hot}\left(T_{hot} - T_{cold}\right) \tag{9}$$

$$A_2 = \frac{A_s k}{\pi D}$$

$$A_3 \frac{dT_{hot}}{dz} = h_{hot}\left(T_{hot} - T_{wall}\right) \tag{10}$$

$$A_3 = \frac{m_{hot} Cp_{hot}}{\pi D}$$

The Q_ι was defined as heat in-leak term by the radiation heat transfer mechanism as follows:

$$Q_\iota = \in \sigma\left(T_a^4 - T_{cold}^4\right) \tag{11}$$

The boundary conditions are as follows:

$$T_{cold}\left(z=0\right) = 21K$$

$$T_w\left(z=0\right) = 21K \text{ and } T_w\left(z=l\right) = 69K$$

$$T_{hot}\left(z=l\right) = 69K$$

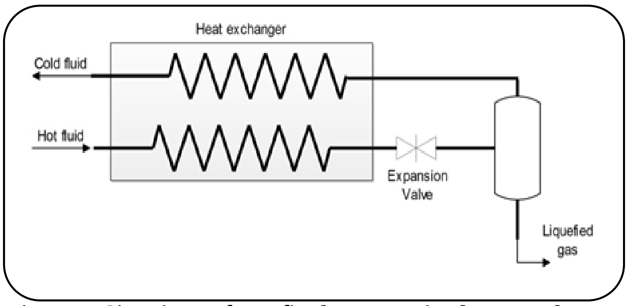

Fig. 3: Situation of a final cryogenic heat exchanger operating in gas liquefier.

Finite Element Method (FEM) was used to simulate the counter current helically coiled tube in the tube heat exchanger. Forward, central, and backward forms of FEM were used to discretize the energy equations in cold fluid, tube wall, and hot fluid respectively. Matlab m-file programming was employed to solve the FEM forms of energy equations by Gauss–Jordan method. The properties of gas (hydrogen) at various temperatures were collected from references. These properties were added to a separate function m-file of Matlab software and this function file was used in the main m-file. The assumptions applied to simulate the problem were as follows:

- The radial distribution of temperature was neglected in gas flows and tube wall.
- The constant tube wall thermal conductivity was applied along the tube.
- The constant convection heat transfer coefficients were assumed for two fluids.
- Conduction and convection heat in-leak terms were neglected (High vacuum conditions).
- Liquefaction efficiency was set 16 percent (only 84 percent of hot fluid comes back as cold fluid showed in Fig. 3)

RESULTS AND DISCUSSIONS

Validating the model was the first step of this work. The aim of the current study was to present a prediction of thermal behavior of final heat exchanger operating in Joule-Thomson hydrogen liquefier in various conditions. So, the working fluid in present work is hydrogen gas but in order to validate the model, helium gas was initially used as working fluid and results were compared with experimental data presented by *Gupta* and *Atrey* [21]. Table 1 gives the parameters used for validating the model.

In the current study, heat in-leak term includes radiation heat transfer in spite of considering linear formulation by other researches. Details for simulating the final heat exchanger operating in hydrogen liquefier were presented in Table 2.

Fig. 4 shows the profiles of hot and cold fluid streams along the length of the heat exchanger. In addition, actual temperatures of fluids presented by *Gupta* and *Atrey* were shown in different points of heat exchanger. As can be seen, temperature profiles obtained from the simulation have acceptable predictions of temperatures compared with experimental results.

Fig. 5 shows the temperature profiles of hot and cold fluid streams along the final heat exchanger operating in hydrogen liquefaction unit. As seen, due to small mass flow rates of fluids, the temperature profiles have different forms of respect to profiles shown in Fig. 4. In order to estimate the heat transfer coefficient within the helically coiled tube, the correlations proposed by *Xin* and *Ebadian* were used as follows [22]:

$$\mathrm{Nu}_{\mathrm{ave}} = \left(2.153 + 0.318\mathrm{De}^{0.643}\right)\mathrm{Pr}^{0.177} \tag{12}$$

$$20 < \mathrm{De} < 2000, \qquad 0.7 < \mathrm{Pr} < 175,$$

$$0.0267 < \frac{d}{D_{\mathrm{coil}}} < 0.0884$$

$$\mathrm{Nu}_{\mathrm{ave}} = 0.00619\,\mathrm{Re}^{0.92}\,\mathrm{Pr}^{0.4}\left(1 + \frac{3.455d}{D_{\mathrm{coil}}}\right) \tag{13}$$

$$5\times10^3 < \mathrm{Re} < 10^5, \qquad 0.7 < \mathrm{Pr} < 5,$$

$$0.0267 < \frac{d}{D_{\mathrm{coil}}} < 0.0884$$

The convection heat transfer coefficient is 2000 W/(m^2.K) for hot fluid respect to 135 W/(m^2.K) for cold fluid. This difference is due to unequal cross section areas, unequal densities, and consequently different fluid regimes for two streams. The tube wall temperature is near the hot fluid temperature at any point of tube length because of higher convection heat transfer coefficient of hot fluid. Longitudinal heat conduction through the tube wall affects the short heat exchanger [1, 5]. As can be seen, in the heat exchanger with a length of 2.8 m, this phenomenon appeared in the small length of the heat exchanger cold end. Longitudinal heat conduction through tube wall resulted in lower temperature of

Table 1: Details of simulation used for validating the model.

Parameters	Values
Working fluid	Helium
Mass flow rates of streams (g/s)	1.8
Length of tube (m)	8
Tube thermal conductivity (W/(m.K))	400
Heat transfer surface area (m^2)	0.16
Overall heat transfer coefficient (W/(m^2.K))	930
Ambient temperature (K)	300
Heat in-leak parameter	0.003
Average Specific heat (J/(kg.K))	5200
Temperature range (K)	80-300

Table 2: Details of simulation for final heat exchanger used in hydrogen liquefier.

Parameters	Values
Working fluid	Hydrogen
Streams arrangement	Counter current
Mass flow rates of hot fluid (g/s)	0.069
Mass flow rates of cold fluid (g/s) (with considering 16 % liquefaction)	0.058
Length of tube (m)	2.8
Tube thermal conductivity (W/(m.K))	400
Hot fluid convection heat transfer coefficient (W/(m^2.K))	2000
Cold fluid convection heat transfer coefficient (W/(m^2.K))	135
Ambient temperature (K)	300
Temperature range (K)	21-69
Inner tube wall thickness (mm)	0.761
Inner tube internal diameter (mm)	1.651
Outer tube internal diameter (mm)	8.001

hot fluid at the cold end. The lower temperature of hot fluid outlet is suitable for the final heat exchanger in hydrogen liquefier because of higher liquefaction efficiency.

Table 3 presents the values of hot fluid and cold fluid outlet temperatures for various tube thermal conductivities. As can be seen, the higher tube wall thermal conductivities result in lower hot fluid outlet temperatures while the cold fluid outlet temperatures are constant for any tube wall thermal conductivity. The duty of final heat exchanger operating in hydrogen liquefier is reduction of hot fluid outlet temperature as low as possible. Therefore, tube wall longitudinal heat conduction has a positive effect on liquefaction efficiency. Longitudinal heat conduction through the tube wall leads to a decrease in temperature difference between hot and cold fluids. So, this phenomenon has a higher effect for the heat exchanger cold or hot end with a higher temperature difference. The temperature difference between hot and cold fluids is small near the heat exchanger hot end, so the cold fluid outlet temperature remains constant for various tube wall thermal conductivities.

Table 3: The effect of tube thermal conductivity on hot fluid and cold fluid outlet temperatures (inner tube internal diameter of 1.651 mm, outer tube internal diameter of 8.001 mm, wall thickness of 0.761 mm, and no heat in-leak).

Tube thermal conductivity W/(m.K))	Hot fluid outlet Temperature (K)	Cold fluid outlet Temperature (K)
20	39.56	67.03
40	39.47	67.03
80	39.30	67.03
160	39.00	67.03
320	38.49	67.03
640	37.70	67.02

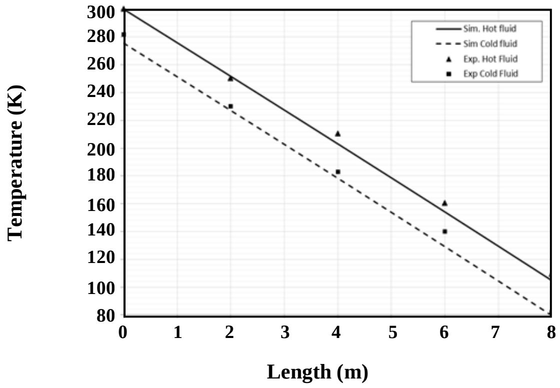

Fig. 4: Temperature profile of hot and cold fluid (helium) streams along the length of the heat exchanger. The experimental data were obtained from reference [21].

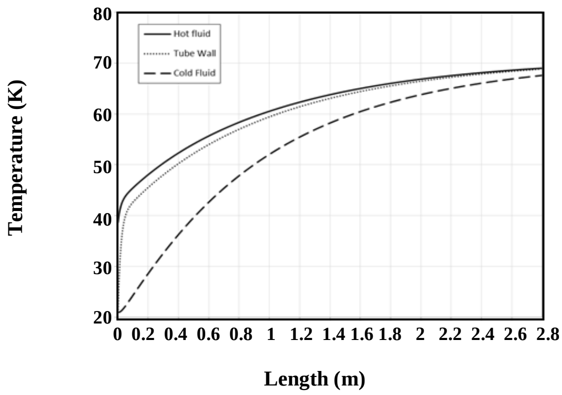

Fig. 5: Temperature profile of hot and cold fluid (Hydrogen) streams along the length of final heat exchanger used in hydrogen liquefier.

Table 4 presents the values of parameters represented in Table 3 considering radiation heat in-leak into the cold fluid. As can be seen, heat in-leak leads to increase in cold fluid outlet temperatures for various tube thermal conductivities. Increase in cold fluid outlet temperatures is constant and small for various tube thermal conductivities. The trend of temperature reduction in the hot fluid outlet is similar to condition with no heat in-leak. However, the values of temperature for the hot fluid outlet (represented in Table 4) are higher than those represented in Table 3. This means that heat in-leak has a minor negative effect on liquefaction efficiency. In addition, heat in-leak leads to increase cold fluid outlet temperature and therefore decrease in temperature approach of the final heat exchanger. Temperature approach decreases with increasing the heat exchanger length because of the higher external surface area exposed to radiation heat transfer and temperature cross will occur finally. Temperature cross must be avoided in heat exchanger thermal design. Fig. 6 shows the values of temperature approach for various length of heat exchanger. For a counter current helically coiled tube in tube heat exchanger with an inner tube internal diameter of 1.651mm and tube wall thickness of 0.761 mm, the length of 3.2 m leads to temperature approach of zero. This means that considering length longer than 3.2 m for mentioned heat exchanger results in temperature cross and negative effect on heat exchanger performance. This event was discussed in section 2.3.

Evaluating the accurate length for cryogenic heat exchanger exposing heat transfer into the cold fluid is an important parameter of heat exchanger thermal design step. The longer length for heat exchangers operating at ambient temperatures results in better performance of heat exchangers, but the longer length of cryogenic heat exchanger leads to temperature cross and the shorter length leads to worse heat exchanger performance. There is a given length for a counter current tube in tube heat

Table4: The effect of tube thermal conductivity on hot fluid and cold fluid outlet temperatures (inner tube internal diameter of 1.651 mm, outer tube internal diameter of 8.001 mm, the wall thickness of 0.761 mm, and radiation heat in-leak).

Tube thermal conductivity W/(m.K))	Hot fluid outlet Temperature (K)	Cold fluid outlet Temperature (K)
20	40.22	67.83
40	40.13	67.83
80	39.96	67.83
160	39.64	67.82
320	39.12	67.82
640	38.29	67.80

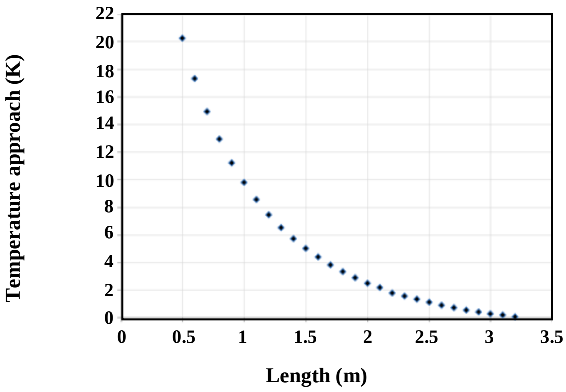

Fig. 6: The values of temperature approach for heat exchanger with given length (inner tube internal diameter of 1.651 mm, outer tube internal diameter of 8.001 mm, the wall thickness of 0.761 mm, and radiation heat in-leak).

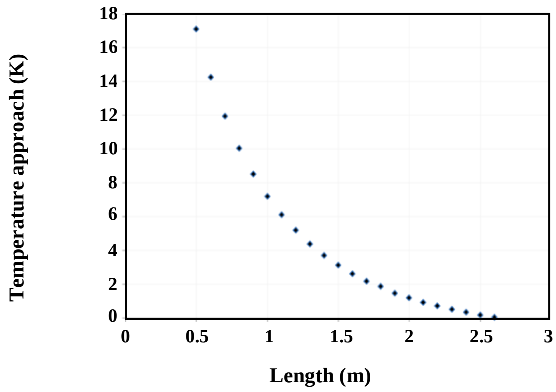

Fig. 7: The values of temperature approach for heat exchanger with given length (inner tube internal diameter of 1.651 mm, outer tube internal diameter of 8.001 mm, the wall thickness of 1.5 mm, and radiation heat in-leak).

exchanger (exposing heat transfer into cold fluid) with given tube wall thickness and mass flow rate to operate at optimum conditions.

Fig. 7 shows the values of the temperature approach for various length of a tube in the tube heat exchanger with an inner tube internal diameter of 1.651mm and tube wall thickness of 1.5 mm. As can be seen, temperature approach of zero occurs at length of 2.6 m with increasing the tube wall thickness from 0.761m to 1.5 mm. This phenomenon is due to increase in heat transfer surface area for cold fluid. In accordance with data presented in Figs. 6 and 7, special considerations must be applied to evaluate accurate length for the heat exchanger operating at low temperatures.

Design considerations for cryogenic heat exchangers must be regarded carefully by engineers to achieve effectiveness as high as possible. In this paper, an attempt was made to present some most important notes to design cryogenic heat exchanger efficiently. Sometimes, neglecting these considerations leads to obtain unreal results and consequently, the predictions do not fit the actual data achieved from experiments. Table 5 presents the effect of considering various parameters on the final heat exchanger operating in hydrogen liquefier as a case study. As can be seen, the percent of liquefaction varies from 33 to 40 by neglecting the radiation heat in-leak. In addition, with regard constant heat capacity ratio versus temperature (as usually considered in parametric studies), the percent of hydrogen liquefaction increase to 41 that never takes place in actual liquefaction plants. Therefore, assumptions applied in the parametric modeling cannot be used as a general assumption for all the cryogenic heat exchangers. The aim of this study was to illustrate the importance of the parameters that are commonly neglected by researchers in the parametric modeling.

Table 5: The effect of considering various parameters on the final heat exchanger operating in hydrogen liquefier.

Regarded considerations	Hot fluid outlet temperature (K)	Cold fluid outlet temperature (K)	Percent of liquefied hydrogen
k= 400 W/(m^2.K) Radiation heat in-leak to cold fluid Variable heat capacities for fluids	40.21	67.81	33 %
k= 400 W/(m^2.K) No heat in-leak Variable heat capacities for fluids	38.27	67.02	40 %
k= 20 W/(m^2.K) No heat in-leak Variable heat capacities for fluids	39.56	67.03	35 %
k= 20 W/(m^2.K) No heat in-leak Constant heat capacities for fluids	37.67	65.58	41 %

CONCLUSIONS

Based on the discussions presented in the previous sections, the following conclusions were obtained:

- The effectiveness factor and degradation factor must be used with special considerations for heat exchanger operating at low temperatures.
- Temperature cross may be occurred in the heat exchanger with cold fluid exposing to heat in-leak.
- Assuming constant heat capacity ratio leads to obtain results with substantial errors.
- Evaluating the accurate length of a counter current tube in tube cryogenic heat exchanger with cold fluid exposing to heat in-leak is an important parameter and considering longer length may result in negative effect in heat exchanger performance.
- Longitudinal heat conduction has no negative effect on cryogenic heat exchanger with long length.
- Longitudinal heat conduction has no effect on the cold fluid outlet temperature.

Considering incorrect assumptions may result in obtaining an unreal prediction of actual conditions for cryogenic heat exchangers.

Nomenclature

T_{cold}	Cold fluid temperature, K
T_{wall}	Tube wall temperature, K
T_{hot}	Hot fluid temperature, K
T_a	Ambient temperature, K
Nu	Nusselt number, dimensionless
De	Dean number, dimensionless
Pr	Prandtl number, dimensionless
d	Diameter of tube, m
Re	Reynolds number, dimensionless
D	Diameter of coil, m
m	Mass flow, kg/s
$\in$	Effectiveness, dimensionless
θ	Maximum temperature difference, K
ΔT	Temperature difference, K
h	Convection heat transfer coefficient, kJ/m^{2}K
cp	Specific heat, kJ/T.kg
Q_ι	Heat in-leak, kJ/m^2
$\in$	Emissivity, dimensionless
σ	Stefan-Boltzmann constant, W/m^{2}K^4
z	Length, m
δ	Temperature approach, K
d	Tube diameter, m
τ	Degradation Factor

Subscript

hot	Hot fluid
cold	Cold fluid
a	Ambient
w	Wall
in	Inlet
out	Outlet
max	Maximum
min	Minimum
ave	Average

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