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Experimental research on heat transfer coefficients for cryogenic cross-counter-flow coiled finned-tube heat exchangers

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ABSTRACT

The aim of present experimental research is to find out the suitable correlations for designing the coiled finned-tube heat exchangers used in cryogenic applications. In order to conduct above experimental study, cross-counter-flow coiled finned-tube heat exchangers were developed in our lab and used in actual refrigeration cycle. The experiments were conducted in the range of effective Reynolds number 500–1900. The effect of diametrical clearance on the prediction of overall heat transfer coefficient is also investigated experimentally. The results from present study were compared in the form of overall heat transfer coefficient. Results of present experimental research indicate that different correlations selected in the study can be used with reasonable accuracy for designing the coiled finned-tube heat exchangers, if they are applied with suitable method of calculation of free-flow cross-sectional area. A more accurate new correlation has also been proposed that fitted experimental data within ±10% error band.

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Recherches expérimentales sur les coefficients de transfert de chaleur dans les échangeurs de chaleur cryogéniques à contre-courant à serpentin

Mots clés : Cryogénie ; Échangeur de chaleur ; Tube aileté ; Tube hélicoïdal ; Hélium ; Expérimentation ; Coefficient de transfert de chaleur

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Nomenclature

A_s	surface area (m^2)
A_{fc}	free-flow area of fins (m^2)
A_{cc}	clearance cross-section area (m^2)
A	total shell side free-flow area (m^2)
A_o	surface area of finless tube of same diameter and length
C	heat capacity rate of fluids defined by the product of $\dot{m}$ and c_p ($W\,K^{-1}$)
c	diametrical clearance (m)
d_i	inner diameter of tube (m)
d_f	fin diameter (m)
d_o	fin root diameter (m)
D_e	mean diameter of shell (m)
D_h	hydraulic diameter(m)
f_s	fin spacing
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_f	fin height (m)
k	thermal conductivity of gas ($W\,m^{-1}\,K^{-1}$)
L	axial length of shell (m)
l	length of finned tube (m)
$\dot{m}$	mass flow rate ($g\,s^{-1}$)
$\dot{m}_f$	actual mass flow rate passes through fins ($g\,s^{-1}$)
n	number of fins per unit length
NTU	overall number of transfer units
p	pitch of tube (m)
Pr	Prandtl number, $\mu c_p/k$
Q	heat transfer from either fluid (W)
Re	Reynolds number, Gd_i/μ
Re_f	Reynolds number based on actual flow as defined in Eq. (32)
s	perimeter of tube (m)
t	mean thickness of fin (m)
T	temperature (K)
T_m	fluid mean temperature (K)
ΔT_{LMTD}	log mean temperature difference (K)
U	overall heat transfer coefficient ($W\,m^{-1}\,K^{-1}$) as defined in Eq. (1)

Greeks

μ	viscosity of fluid
ρ	density of fluid ($kg\,m^{-3}$)

Subscripts

c	cold fluid
h	hot fluid
i	inner
o	outer
in	inlet
out	outlet
t	tube
s	shell
spc	by projected area method
svc	by free volume concept
shc	by hypothetical cylinder concept

1. Introduction

Heat exchangers are one of the most critical components of any cryogenic system such as helium liquefiers/refrigerators. Design of these cryogenic heat exchangers demands the consideration of various loss mechanisms (Gupta and Atrey, 2000; Gupta et al., 2007a). These heat exchangers must be able to realize small temperature difference between fluid streams consistent with large heat exchange surface per unit volume. The cross-counter-flow coiled finned-tube heat exchangers are one of the choices for these systems and they are still used in small to medium helium size liquefiers/refrigerators and JT cryocoolers. These heat exchangers were first used by Collins in his liquefier (Collins, 1947). From the system performance point of view, sizing of these heat exchangers plays an important role. The most optimum size of these heat exchangers is required to

- minimize the cool down time of the system
- minimize the refrigeration loss to cool the unit
- minimize the radiation loss, and to
- reduce the cost of the system

There are two well known design methods for conventional heat exchangers i.e. the log mean temperature difference (LMTD) method and the effectiveness-NTU method (Kays and London, 1964). These two methods can also be applied for designing the coiled finned-tube heat exchangers.

In both of the methods, the overall heat transfer coefficient (U) between two streams is required for estimating the heat transfer surface area of a heat exchanger. The overall heat transfer coefficient is composed of three components; the high pressure hot fluid convection component, transverse wall conduction component and low pressure cold fluid convection component. It is, therefore, simply represented by the following equation for a coiled finned-tube heat exchanger:

$$\frac{1}{U} = \frac{1}{h_h s_i} + R_w + \frac{1}{h_c s_o} \tag{1}$$

In coiled finned-tube heat exchangers, the hot stream flows through the finned tubes and it is at higher pressure. There is an efficient heat exchange between the hot fluid and the inner surface of the tube. Therefore hot stream has least convective resistance ($1/h_h s_i$). While the cold fluid at lower pressure flows over the finned tubes in the shell of heat exchanger. Therefore, the typical value of shell side heat transfer coefficient is less and in practical applications, this is the most dominant resistance in estimations of overall heat transfer coefficients. Estimation of tube side heat transfer coefficient (h_h) is relatively simple and estimated values of it do not affect much the accuracy of calculations of overall heat transfer coefficients.

For precise rating or sizing calculations of heat exchangers, an accurate evaluation of shell side heat transfer coefficient is an important aspect. These heat exchangers have been in use since half of the century but still a very little information is available in open literature regarding the estimations of shell

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