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International Journal of Heat and Mass Transfer 51 (2008) 4926–4939

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Two-phase pressure drops in a helically coiled steam generator

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Received 26 February 2007
Available online 21 April 2008

Abstract

An experimental investigation regarding two-phase diabatic pressure drops inside a helically coiled heat exchanger have been carried out at SIET thermo-hydraulics labs in Piacenza (Italy). The experimental campaign is part of a wide program of study of the IRIS innovative reactor steam generator. The test section consists of an AISI 316 stainless steel tube, 32 m length, 12.53 mm inner diameter, curved in helical shape with a bend radius of 0.5 m and a helix pitch of 0.8 m, resulting in a total height of the steam generator tube of 8 m. The explored operating conditions for two-phase flow experiences range from 192 to 824 kg/m^2 s for the mass flux, from 0 to 1 for the quality, from 1.1 to 6.3 MPa for the pressure, from 50 to 200 kW/m^2 for the heat fluxes. A frictional two-phase pressure drops correlation, based on an energy balance of the two-phase mixture and including the 940 experimental points, is proposed. Comparison with existing correlations shows the difficulty in predicting two-phase pressure drops in helical coil steam generators.

Keywords: Coils; Helically coiled pipes; Steam generator; Two-phase flow; Pressure drops

1. Introduction

Heat exchangers are one of the most common technological device applied in power, chemical and food processing industries. Many options are available for obtaining compactness and efficiency in exchanging thermal power. In the field of tubular heat exchangers one possible way for reducing the space occupied by the exchanger is by bending tube axis in helicoidal shape. This option is particularly suitable when construction simplicity is needed and when the geometry of the place in which the exchanger has to be housed is the cylindrical one. Many advantages derive from this disposition, such as an excellent behaviour in presence of severe thermal expansions; in fact the helical shape allows the exchanger to behave as a spring, thus accommodating the stresses due to the expansions. Moreover the exchanger has the possibility of working locally in the cross-flow disposition and globally in counter-flow (the so called cross-counter principle applied in many shell and tube exchangers), thus combining all the positive aspects of the two arrangement. Helically coiled heat exchangers in the multi-start disposition has no internal baffle leakage problems and are little sensitive to flow maldistributions [1]. However, some difficulties could rise in the manufacturing process and in the bundle fabrication phase, thus increasing costs.

In the past many industrial applications of helically coiled tube-bundle heat exchangers have been realized: natural gas liquefaction apparatus [1], solar energy concentrator receivers [2] and many steam generators for nuclear power plants (e.g. Otto Hahn nuclear ship, SuperPhoenix fast reactor, AGR , Fort St. Vrain HTGR, THTR-300 etc.). Up to now there are several projects in nuclear industry for electricity production involving helically coiled steam generators [3].

The presence of two new geometrical variables, such as coil diameter and coil pitch, renders single-phase thermo-hydraulics phenomena in coiled ducts more complex than

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0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2008.02.034

Nomenclature

A	inner cross sectional area of the tube (m^2)
D	helix diameter (m)
d	tube inner diameter (m)
f	friction factor (Fanning)
F	parameter in Ruffel's correlation
G	mass flux ($kg/m^2 s$)
g	gravity acceleration (m/s^2)
K	quality multiplier
L	tube length (m)
MEM	mean error
N	number of experimental points
p	pressure (Pa)
R_p	reduced pressure
Re	Reynolds number
RMS	root mean square error
s	curvilinear abscissa (m); tube perimeter (m)
v	specific volume (m^3/kg)
x	thermodynamic equilibrium quality
y	parameter in Ruffel's correlation
z	vertical elevation (m)
Greek symbols	
α	volumetric gas fraction (void fraction)
τ	tangential stress (Pa/m^2)
ρ^*	photographic density (kg/m^3)
Δ	difference
ΔP_0	frictional pressure drops with liquid flowing alone with total flow rate
μ	viscosity (Pa $\times$ s)
ξ	two-phase multiplier in Chen's correlation
θ	tube inclination (to horizontal direction) (deg)
ρ	density (kg/m^3)
ψ	two-phase multiplier in Guo's correlation
Φ_{lo}^2	two-phase multiplier
Subscripts	
a	accelerative
c	coil
calc	calculated value
E	referred to energy balance
exp	experimental value
f	frictional
g	vapour phase; gravitational
l	liquid phase
lo	liquid only
m	mixture (referred to the homog. model)
M	referred to momentum balance
str	straight
tp	two-phase
w	wall

in straight ones. However, as a result of relatively wide experimental campaigns, correlations of pressure drops and heat transfer coefficients of acceptable validity are available mainly in the single-phase regime [4]. Moreover, as happens in straight tubes, two-phase flow behaviour is further complicated, also because besides pressure drops and heat transfer coefficients, the knowledge of dry out power and thermo-hydraulics instabilities is needed. In particular, no general correlation for two-phase pressure drops in coils, valid for a wide range of physical parameters, is available till now, while a certain number is proposed for specific and limited ranges. However, none of them tries to correlate pitch effect, even if it is supposed to be in general moderate.

In the present work single and two-phase pressure drops in diabatic conditions are measured in a helically coiled 32 m long steam generator electrically heated with inner diameter of 12.53 mm, coil diameter of 1 m and 0.8 m of pitch. This tube is representative of the steam generator foreseen for the IRIS reactor [5]. The explored operating conditions for two-phase diabatic pressure drops range from 195 to 824 $kg/m^2 s$ for the mass flux, from 0 to 1 for the quality, from 1.1 to 6.3 MPa for the pressure, from 50 to 200 kW/m^2 for the heat flux. Two-phase pressure drops data reduction allowed to extend the range of explored conditions offered in free literature and a simple correlation for their prediction is proposed in the paper.

The synthesis of the data coming from the experimental campaign gave also a correlation for calculating single-phase Fanning friction factor in the tested tube up to Reynolds number of 6.34×10^5. This result allow to fill the shortage of informations in literature regarding high Reynolds numbers single-phase frictional pressure drops in coiled tubes.

2. Review of pressure drops correlations in helical tubes for two-phase flow

In the last few years Chinese researchers has given an important contribution to the knowledge of two-phase pressure drops in helically coiled heat exchangers. In a recent article Guo et al. [6] have compared the available correlations, showing the difficulties of predicting two-phase pressure drops by different formulas. The authors have tested two electrically heated coiled steam generators with several tube axis inclinations, putting in light the strong effect of this parameter on two-phase pressure drops. The investigated conditions were: steam–water mixture, tube of 10 mm of inner diameter, D/d of 13 and 25; pressure 0.5–3.5 MPa, mass flux 150–1760 $kg/m^2 s$, quality 0–1.2. They obtained the following correlation: