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# Boiling pressure drop and local heat transfer distribution of helical coils with water at low pressure

B.K. Hardik, S.V. Prabhu*

*Department of Mechanical Engineering, Indian Institute of Technology, Bombay, India*

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ABSTRACT

The objective of the present work is to study the influence of curvature on local boiling heat transfer coefficient and two-phase pressure drop in helically coiled tubes with water as the working medium. In helically coiled tubes, the geometric parameters like pipe diameter and coil diameter vary the curvature and hence secondary flow which affects the heat transfer distribution and pressure drop. The present work investigates the characteristics of flow boiling in helically coiled tubes. Very less information is available on the influence of curvature on flow boiling system. The local wall temperature is measured not only in the axial direction (along the length of coil) but also in the circumferential direction using thermal imaging technique. Experiments are performed with six helically coiled test sections made of SS 304 tubes having inner diameters varying from 6 to 10 mm. The coil diameter to the tube diameter ratio ranges from 14 to 58 and coil pitch is 50 mm. The effect of geometric and operating parameters like tube diameter, coil diameter, heat flux and mass flux on local boiling heat transfer coefficient and two-phase pressure drop is analysed. In the subcooled region and in a low quality region, boiling heat transfer coefficient in helical coils is much higher (12%–100%) than in straight tubes. However, in a high quality region, the boiling heat transfer coefficient in helical coils is same as in straight tubes. A correlation is suggested for two-phase pressure drop in helical coils.



## 1. Introduction

The heat transfer through helical coil is better choice where the space for heat exchanger is limited and difficult to lay straight pipe. Literature on single phase flow through helical coil shows the enhancement in heat transfer coefficient due to secondary flow. Compact design, easy manufacturing and high heat transfer efficiency compared to straight tube make the helical coil favourable for heat exchanger application. Helical coiled steam generators are of major interest in the nuclear industry for electricity production. Boiling phenomena is studied well for flow inside a straight tube. However, boiling mechanism inside helical coils may differ from straight tubes due to phase separation with low density vapour being inner side and high density liquid on outer side of curved tube or the appearance of thin liquid film on circumference caused by the gravity and centrifugal forces. Thus, a large temperature distribution may occur on the circumference of tube wall. This may affect the heat transfer performance and can cause dryout of liquid film on inner side of curved tube. Therefore, a detailed study of the wall temperature distribution and heat transfer characteristics in the helical coils is required. The ranges for subcooled and saturated flow strongly depend on the saturation temperature and hence saturation pressure. In the saturated boiling region, distribution of local bulk fluid temperature is dependent on the pressure drop distribution. To predict the local heat transfer coefficient accurately, it is necessary to know the saturation pressure at different points in the test sections. The present section reviews the characteristics of two-phase pressure drop and heat transfer coefficient in different region i.e. subcooled and saturated, of flow boiling. Published correlations of flow boiling heat transfer in helical coils are collated. This review presents the status of the research in the area of two-phase pressure drop in helical coils.

### 1.1. Review of flow boiling heat transfer inside helical coils

Naphon and Wongwises [1] and Vashisth et al. [2] conducted a review on single and two phase flow in curved tubes. They state that, in spite of wide range of applications of curved geometry in industrial devices, there is a lack of fundamental knowledge and

* Corresponding author. Department of Mechanical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai, Pin: 400 076, India.

*E-mail addresses:* h.kothadia@gmail.com (B.K. Hardik), svprabhu@iitb.ac.in (S.V. Prabhu).

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**Nomenclature**

*Symbol*

| | |
|---|---|
| $Cp$ | Specific heat at constant pressure $J/kgK$ |
| $d$ | Diameter of tube $m$ |
| $D$ | Diameter of helical coil $m$ |
| *Deviation* | $(C_{cal} - C_{exp})/C_{exp} \times 100$ % |
| *Enhancement* | $(C_{Helical} - C_{Straight})/C_{Straight} \times 100$ % |
| $f$ | Friction factor |
| $G$ | Mass flux $kg/m^2s$ |
| $g$ | Gravitational constant $m/s^2$ |
| $h$ | Heat transfer coefficient $W/m^2K$ |
| $i$ | Enthalpy $J/kg$ |
| $k$ | Thermal conductivity $W/mK$ |
| $L$ | Length $m$ |
| $M$ | Molecular Weight $g/mol$ |
| $\dot{m}$ | Mass flow rate $kg/s$ |
| $P$ | Pressure $N/m^2$ |
| $Q$ | Heat supply $W$ |
| $q''$ | Heat flux $W/m^2$ |
| $T$ | Temperature |
| $x$ | Quality of steam |
| $X, X_{LM}$ | Lockhart Martinelli parameter $X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$ |

*Greek*

| | |
|---|---|
| $\varnothing$ | Two phase flow multiplier $\varnothing^2 = \frac{\Delta P_{TP,fric}}{\Delta P_{1P}}$ |
| $\mu$ | Dynamic viscosity $N\cdot s/m^2$ |
| $\rho$ | Density $kg/m^3$ |
| $\sigma$ | Surface tension $N/m$ |

*Subscript*

| | |
|---|---|
| *acc* | Acceleration |
| *b* | Bulk |
| *f* | Film |
| *fg* | Fluid to gas |
| *fric* | Friction |
| *g* | Gas |
| *h* | Heated |
| *l* | Liquid |
| *lo* | Liquid only |
| *P* | Phase |
| *sat* | Saturated |
| *SC* | Subcooled |
| *sys* | System |
| *T* | Total |
| *TP* | Two phase |
| *tt* | Turbulent liquid and Turbulent vapour |
| *lt* | Laminar liquid and Turbulent vapour |
| *w* | Wall |

*Abbreviation*

| | |
|---|---|
| *HTC* | Heat Transfer Coefficient |

*Dimensionless number*

| | |
|---|---|
| *Bo* | Boiling number $Bo = q''/Gi_{fg}$ |
| *Ja* | Jakob number $Ja = Cp\cdot\Delta T_{sc}/i_{fg}$ |
| *Nu* | Nessult number $Nu = h\cdot d/K$ |
| *Pr* | Prandtl Number $Pr = \mu\cdot Cp/K$ |
| *Re* | Reynolds number $Re = 4\dot{m}/\pi d\mu$ |

literature studied on curved tubes compare to that of straight tubes. Few works on the two-phase heat transfer characteristics in helically coiled tubes are reported. There are contradictory conclusions reported in the literature on the influence of the secondary flow on the heat transfer coefficient. Several authors report almost no influence of secondary flow and suggest straight tube heat transfer correlation for helical coils. However, few authors report enhancement of heat transfer due to the secondary movement of bulk fluid and report a correlation for heat transfer for helical coils.

The overview of literature studied on boiling heat transfer in helical coils is given in Table 1. It may be observed that most of the works show that the straight tube heat transfer correlations slightly underpredict in comparison with the experimental data of helical coils. Table 1 shows that the boiling mechanism inside helical coils is not conclusive. Kozeki et al. [3], Hwang et al. [4], Chung et al. [5] heat transfer experiments on water and Ami et al. [6] experiments with liquid nitrogen at saturated boiling condition shows nearly constant value of heat transfer coefficient with increase of thermodynamic equilibrium quality. Thus, nucleate boiling may be a dominant phenomenon. However, others suggest an increase in heat transfer coefficient with quality. Hence, boiling mechanism includes both nucleate boiling and convective boiling. Available correlations of helical coil heat transfer coefficient are collated in Table 1.

### 1.2. Review of two phase pressure drop inside helical coils

Compared to heat transfer, reasonably large body of literature is available on two-phase pressure drop in helical coils. The overview of literature studied on two-phase pressure drop in helical coils is given in Table 2. Most of the literature on two-phase pressure drop reported an increase in the pressure drop compared to that of straight tube. Literature on two-phase pressure drop divides into gas liquid two-phase flow (Adiabatic) and boiling two-phase flow (Diabatic). Most of the studies on two-phase pressure drop are referred gas liquid co-current flow. Less work is done on boiling pressure drop in helical coils. Most of the authors in the literature reported their own correlation for two-phase pressure drop. This may be because of the complexities involved in studying the two-phase flow in helical coils.

Literature review on two-phase pressure drop concluded that pressure drop in helical coils can correlated with Lockhart-Martinelli parameter. Wongwises and Polsongkram [12], Nariai et al. [9] and many others derived their correlations in the form of Lockhart-Martinelli parameter for diabatic and adiabatic flow. Enhancement of pressure drop in two-phase flow is almost same as in single phase flow. Available correlation of diabatic two-phase pressure drop and the detail of operational and geometry experiments condition are collated in Table 2. Few important correlations for adiabatic two-phase pressure drop are also presented in Table 2.

Following are the conclusions that may be drawn from literature review.

- No work is reported on subcooled heat transfer in helical coil
- No literature is available on the circumferential variation in the wall temperature distribution and heat transfer distribution.