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A scheme of correlation for frictional pressure drop in steam–water two-phase flow in helicoidal tubes

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HIGHLIGHTS

- A correlation for two-phase frictional pressure drops in helical pipes is proposed.
- The correlation is developed with experimental data from different coil geometries.
- Comparison with other correlations shows improvement of the accuracy.
- The correlation holds over an extended range of parameters.
- The scheme of correlation accounts for the essential effect of the coil diameter.

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ABSTRACT

In the nuclear field, helically coiled tube steam generators (SGs) are considered as a primary option for different nuclear reactor projects of Generation III+ and Generation IV. For their characteristics, in particular compactness of the component design, higher heat transfer rates and better capability to accommodate thermal expansion, they are especially attractive for small-medium modular reactors (SMRs) of Generation III+.

In this paper, starting from two existing databases, a new correlation is developed for the determination of the two-phase frictional pressure drop. The experimental data cover the ranges 5–65 bar for the pressure, 200 to 800 $kg/m^2\,s$ for the mass flux and 0 to 1 for the quality. Two coil diameters have been considered, namely 0.292 m and 1.0 m. The coil diameter in particular is crucial for a correct estimation of the two-phase frictional pressure drop. Actually, no general correlation reliable in a wide range of coil geometries is available at the moment. Starting from the noteworthy correlation of Lockhart and Martinelli, corrective parameters are included to account for the effect of the centrifugal force, introduced by the helical geometry, and the system pressure. The correlation is developed with the aim to obtain a form of general validity, while keeping as low as possible the number of empirical coefficients involved.

The average relative deviation between the correlation and the experimental data is about 12.9% on the whole database, which results the best among numerous literature correlations. In addition, the new correlation is characterized by an extended range of validity, in particular for the diameter of the coil.

1. Introduction

Helical pipes and heat exchangers with helical coils are extensively used in different industrial fields and applications, including hot water heaters, chemical process reactors, industrial and marine boilers, cooling systems and blood oxygenators, among many others (Bejan and Kraus, 2003). They provide a substantial improvement in heat and mass transfer rates and, most important for boiling and evaporation, a significant enhancement of the critical heat flux (Bejan and Kraus, 2003). Despite helical pipes have been applied in the past for Steam Generators (SGs) in nuclear power plants (Advanced Gas Reactor (AGR), Fort St. Vrain HTGR, THTR 300, Otto Hahn nuclear ship), at the moment they are experiencing a renewed interest in the nuclear field. In fact helical pipes are considered as a primary option for SGs of different nuclear reactor projects of Generation III+ and

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Generation IV, aiming at improving safety, sustainability, performance and costs of nuclear power plants through the adoption of new technological solutions and the improvement of single plant components. Helical tube heat exchangers offer better heat transfer characteristics, improved capability to accommodate tube thermal expansion and compactness of the design (Cinotti et al., 2002). Among other projects, helical pipes are very attractive for Small-medium Modular Reactors (SMRs) of Generation III+, which require in particular compactness as all the primary system components are located inside the reactor vessel (Kim et al., 2003; Carelli et al., 2004).

Many researchers have focused their attention on the thermal hydraulic characteristics of the flow inside helical pipes: the various works available in literature have been discussed in different comprehensive reviews (Berger et al., 1983; Shah and Joshi, 1987; Naphon and Wongwises, 2006). Concerning the single-phase flow, advances have been made in the understanding of the physical phenomena that characterize the fluid dynamics and the heat transfer. As a matter of fact, the literature provides different tools able to predict with a high degree of accuracy the heat transfer coefficients and the pressure drop. Differently, for the two-phase flow the subject is much more complex. Consequently, more research is needed to improve the anyway remarkable results already achieved on fields such as the two-phase pressure drop, the two-phase heat transfer and the thermal crisis. In particular, this paper is focused on the prediction of the two-phase frictional pressure drop. As already reported by Santini et al. (2008), although a significant number of correlations have already been developed, no general correlation reliable in a wide range of geometrical parameters and operating conditions is available at the moment. On the contrary, several of them are only valid within a limited range of parameters. In addition, many show a complicated form, including numerous empirical coefficients determined by multivariable regressions (e.g. Ruffel (1974), Guo et al. (2001) and Zhao et al. (2003)).

In this paper, a new correlation for the two-phase frictional pressure drop is developed, with the aim to expand its range of validity with respect to existing correlations, reaching a satisfactory accuracy in an extended range of conditions. The starting point is the noteworthy Lockhart and Martinelli (1949) correlation, developed for straight horizontal tubes, since it has been used successfully in many circumstances and has been reported by several authors to work fairly well also in helical geometry. Proper modifications are introduced starting from the analysis of the experimental results and their physical interpretation, while keeping the number of the needed empirical constants as lowest as possible, to avoid complicated formulations. The new correlation is first applied to the same database reported by Santini et al. (2008) and collected in an experimental facility installed at SIET laboratories, in Piacenza, Italy. As a first check, also the correlation proposed by Friedel (1979) for straight vertical pipes is modified with the same scheme of correlation. At a later stage, also the experimental data from the work of Zhao et al. (2003) are included in the database. The global database includes measurements from different values of the coil diameter, essential to develop a correlation applicable in an extended range of conditions and able to reproduce the influence of the helical geometry. The accuracy of the new correlation is finally compared with the results of other correlations available in literature.

2. Literature review

In the past, different authors handled the problem of the two-phase frictional pressure drop in helical pipes, starting from own experimental results to derive proper correlations. Early works on the subject reported in literature, due to Rippel et al. (1966), Owhadi et al. (1968), Banerjee et al. (1969), Akagawa et al. (1971) and Katsuri and Stepanek (1972), found a satisfactory agreement between their experimental data and the original or slightly modified correlation of Lockhart and Martinelli, developed for horizontal straight pipes. All the authors reported maximum relative errors always lower than 50% and average relative errors between 20% and 40%, in a large number of different coils and operating conditions. Other authors started their analysis from models and correlations developed for straight pipes. Awwad et al. (1995) and Xin et al. (1996,1997) modified the original form of the Lockhart–Martinelli multiplier as a function of the Froude number Fr and the pipe diameter to coil diameter ratio (d/D). They reported maximum deviations always lower than 35% for circular and annular channels, with both vertical and horizontal orientations. Nariai et al. (1982) adopted the correlation for straight tube due to Martinelli and Nelson (1948), evaluating the single-phase pressure drop with the Ito (1959) correlation. Comparison with data from a test rig of an integrated type marine water reactor showed agreement within 30%. Slightly better results were obtained using a modified version of the correlation proposed by Kozeki et al. (1970), based on a different form of the two-phase pressure drop multiplier. Czop et al. (1994) considered experimental data obtained with adiabatic water-SF6 mixture in a helically coiled tube and found better agreement with the Chisholm correlation (Chisholm and Sutherland, 1969) than using the Lockhart and Martinelli method. Other models proposed for straight tubes have been tested by different authors, in particular the Dukler approach (Dukler et al., 1964) in Katsuri and Stepanek (1972) and Baroczy (1965) and Thom (1964) correlations in Nariai et al. (1982), finding always higher errors with respect to the Lockhart and Martinelli correlation.

Among the correlations developed without referring to straight channel models, Ruffel (1974) proposed a different form of the liquid only friction multiplier, based on experimental results in three different coils tested to study the AGR secondary system. Unal et al. (1981) developed a model to calculate frictional pressure losses after testing three different coils heated by a sodium flow, in order to investigate the behaviour of a liquid metal fast breeder reactor. Chen and Zhou (1981), based on a steam–water mixture flowing in three different helical coils, obtained a relation for the liquid only friction multiplier including the effect of the void fraction α and the d/D ratio. Guo et al. (2001) proposed a correlation for the liquid only friction multiplier based on the data from two helical tubes with four different axial inclinations of the helix. Authors reported maximum relative errors always lower than 40%. A liquid only friction multiplier correlation was developed for horizontal helically coiled pipes by Zhao et al. (2003), reaching an average relative error within 15%. Mandal and Das (2003), starting from data relative to coils with different geometrical parameters, proposed an empirical correlation based on various dimensionless quantities to reach an average relative error of about 15%. Santini et al. (2008) completed an experimental investigation on the helically coiled tube of a Generation III+ SMR project, the IRIS reactor (Carelli et al., (2004). The empirical correlation proposed correlates the frictional pressure drop with flow rate, mixture density and tube diameter. In addition, it accounts for the mixture quality by a cubic function. The authors indicate an average error of about 9%, with about 95% of the data within the range ±15%. However, the correlation does not account for the effect of the coil curvature; therefore, it seems difficult to extend its range of applicability, in particular with respect to the coil diameter. Actually, it is a best-fit of experimental data, coming from an engineering approach useful for the design of the reactor. Since the large number of considered correlations are representative of many different experimental conditions