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Flow pattern change in horizontal rectangular laterally ribbed ducts through alteration of the ribs thickness and pitch

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ABSTRACT

Experiments were conducted on two-phase flow in laterally ribbed rectangular ducts. Air–water adiabatic flow at atmospheric pressure and room temperature was driven through a 3.6 m long rectangular ribbed test section with cross-section of 100 × 50 mm. To investigate the effect of rib thickness and pitch on flow pattern diagrams and transition boundaries, nine various rib arrangements were implemented with thicknesses of 2, 4 and 8 mm and pitches of 50, 60, and 80 mm. Unlike non-ribbed rectangular duct, lateral rib arrangement did not allow any stratified flow to occur. However wavy, plug and slug flows were parallel in both flow conditions, rib existence caused explicitly coarser pattern shapes. Increasing the rib thickness, while keeping the pitch constant, results in different flow patterns to occur as well as dramatic changes in boundaries positions and shapes. On the other hand, as pitch shifts up at a constant rib thickness, one can notice the duplication of almost identical flow patterns and their boundaries however, boundary values undergo tangible changes. Consistent attention was paid to conditions under which wavy pattern zone extends while intermittent flow zones were avoided. Studies concerned ribbed duct are of major applicable value to designing and enhancing heat transfer systems.

1. Introduction

During past decades, usage of ribbed, finned, and, corrugated passages has increased as an effective passive method of enhancing heat transfer of various industrial systems. The widespread use of ribbed ducts in different applications such as heat exchanger, turbine blades, and ventilation encouraged numerous studies on the both single and two-phase flow in conduits. Most studies focus on the hydrodynamic and thermal parameters of the flow namely friction factor and Nusselt number. The concentration is mainly on the enhancement of thermal performance, while a few studies were carried out concerning the governing causes and influential operators, which play key roles to such performances.

Considering single-phase heat transfer systems, many numerical and experimental studies conducted to evolve today's comprehensive knowledge of flow thermal and hydrodynamic behavior. Gradeck and Lebouche (1998) studied the single-phase flow structure inside two-dimensional and three-dimensional corrugated channels using an electrochemical method. They indicated different flow zones inside each type of channels, which contribute to specific flow behaviors. Gradeck et al. (2005) pursued their study by investigating the contribution that each of these zones has on the local heat transfer in both laminar and turbulent flows. In a similar attempt, Lin et al. (2011) conducted experiments as well as producing a numerical code to determine the heat transfer behavior of laminar flow passing through circular channels with internally sinusoidal fins. Their study showed the insufficiency of presuming linear temperature distribution along the flow direction because of axial heat conduction in tube wall.

Rib roughening was employed by Han et al. (1978) to study the effect of such obstacles on friction factor and Nusselt number. Their universal study included sixteen different geometries, which yielded various applicable results including the identification of ribs with 45° angle of attack as the most efficient arrangement. Further experimental studies, scrutinizing the effects of rib geometry and arrangements in rectangular ducts on the flow characteristics, were pursued by Han and Park (1988), and Tanda (2004, 2011). Hsieh and Lin (1993) studied heat transfer in finned tube annuli. Enhancement of heat transfer in helically ribbed tube with double tape inserts was conducted by Promvonge et al. (2012). Square and triangular ribbed channels were considered by Chang et al. (2011) and Promvonge et al. (2010) respectively.

In addition to experimental studies, various numerical works were carried out to find possible augmentations to heat transfer by modifying the flow passage geometry. Changes in flow friction coefficient and Nusselt number due to alteration in fin numbers and relative rib height were studied by Rustum and Soliman (1990). Results confirmed the strong influence of changing rib

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height and number on the intensity of secondary flow, which consequently affects Nusselt number and friction factor. Liou et al. (1993) employed k–ε–A PDM turbulence model to assess the consequences of installing periodic ribs on one of the principal walls in the turbulent flow. They introduced a correlation, which encompasses the effects of Reynolds number, rib spacing, and rib height on the average heat transfer coefficients. Various shapes of lateral longitudinal ribs viz. S, V, and Z shapes in circular blocked-core tube were analyzed by Wang et al. (2009). They used commercial software Fluent to evaluate the shape effect on the rib performance. Recent numerical studies were conducted by Desrues et al. (2012) and Ma et al. (2012). The former study assessed the alternated opposite arrangement for ribs inside rectangular channel while the later investigated the deviations which occur in heat exchanger performance in high temperature operating conditions comparing to normal operational conditions.

One of the primary essential steps in understanding two-phase flow is to distinguish its various flow patterns. Each specific flow pattern anticipates the pressure drop, void fraction, and heat and mass transfer mechanisms behind that distribution of the phases, called patterns or regimes. Thus, flow patterns and their transitions into another one greatly dominate and truly precede the further calculations and modeling of two-phase flows. Two-phase maldistribution reduces the thermal and hydraulic performance of compact heat exchangers with parallel flow circuits and may cause the apparition of dry-out zones in evaporators (Ahmad et al., 2009). Deep insight into the consequences of various modifications to flow conduit by means of ribs or inserts guides the complementary researches to more comprehensive and general studies.

Zarnett and Charles (1969) carried out the first investigation on flow patterns in ribbed ducts. It is clear from their description that to reach desirable swirling flow, a minimum liquid superficial velocity should be reached. They also claimed that pitch to diameter ratio makes no significant change in positions of flow regimes.

Weisman et al. (1994) tested flow regimes in ribbed ducts to assess their influence on the augmentation of heat transfer and critical heat flux (CHF) in boilers. They confirmed the existence of a critical liquid velocity before assurance of swirling flow at any flow quality. Through comparison of their data with those of Zarnett and Charles (1969), they attributed the formation of bubble flow in Zarnett and Charles experiments to square cross section of ribs implemented in their work. Weisman et al. (1996) pursued their study on ribbed ducts by studying vapor–liquid R-113 two-phase flow. Two flow maps were produced and transition boundaries were compared with their previous study which air and water were used as working fluids. They ascribed the development of swirling flow in helically ribbed duct to centripetal force caused by swirling flow paths.

The first study on vertical counter-current flow in ribbed duct was conducted by Kim et al. (2001).They observed that inserted ribs induce disturbance into the flow, which distorts the bubble and slug motion and shape appreciably when compared to same regimes observed in smooth rib-free ducts.

Heat transfer performance, pressure drop, and flow patterns for three different refrigerants viz. R-22, R407C, and R134a experiencing condensation were investigated by Olivier et al. (2007). They produced one flow map for the three refrigerants that depicts the range of vapor quality and mass flux. It can be inferred from the map that replacing the smooth tube with other configurations seriously delays the transition from annular to intermittent flow.

Ansari and Arzandi (2011) focused their study on the effects of rib height and the location of the ribbed wall in a duct on flow patterns and transition boundaries. Maintaining the fixed pitch of 50 mm, ribs with 1, 2 and 4 mm thicknesses were adhered to air side, water side and both air and water side walls to discover the effect of rib thickness and arrangement on the flow patterns. Through comparison with the non-ribbed rectangular duct, they deduced that their implemented rib arrangements make no variation in the observed flow patterns.

Gradeck and Lebouche (2000) carried out a research on 2D and 3D corrugated plates using water and nitrogen as working fluids. Keeping the amplitude and pitch of corrugation at fixed 20 and 65 mm through the tests, they reported stratified and wavy flows as dominant observed flows.

Air–water flow in vertical sinusoidal wavy channels were observed and studied by Nilpueng and Wongwises (2006). However pitch and amplitude of sinuses maintained constant, they applied three phase shifts of 0°, 90° and 180° between the sidewalls to examine the associated influences on flow pattern and pressure drop of the flows.

Further attempts to understand the transport mechanisms in two-phase flow in ribbed passages were undertaken by Carey (1993). He studied the divergences that arise due to small-scale size of passages and the strong role of surface tension in such phenomena. Akhavan-Behabadi et al. (2009) fulfilled a study on the trend of heat transfer and pressure drop due to placing coiled wire ribs of various pitches and thicknesses under different heat fluxes. Zurcher et al. (2002) introduced a modified flow map for evaporation in horizontal tubes for common refrigerants. Using the transition models and flow maps proposed by previous authors, a modified flow map was proposed. Cheng and Chen (2007) investigated the upward water–kerosene flow pressure drop in a vertical spirally internally ribbed tube, uniformly heated to obtain flow boiling test conditions. Cheng and Xia (2002) studied the CHF behavior of spirally internally ribbed tube under high-pressure conditions for vertical upward water flow. More researches on CHF evaluations under different experimental conditions in ribbed ducts were accomplished by Whalley (1979) and Kim et al. (2005).

Although numerous works and experiments were conducted on two-phase flow in differently ribbed ducts, dominant portion is dedicated to assessment of thermal and hydrodynamic behaviors of the flow. Hence, one may scarcely find researches done on precise investigation of critical flow pattern issue in open literature. Table 1 shows the experimental conditions and ribbing geometry and arrangements used by previous authors to investigate their corresponding effects on flow regimes. Although precious studies were conducted, introduced transition criteria and flow regime maps are not applicable to present study directly. It is because of completely different channel cross section and rib arrangements and geometries, employed by previous researches. However, authors attempted to compare the obtained results from the present work to previous conclusions where convenient.

In the present study, the maximum focus is shed on flow patterns, which occur in the horizontal internally laterally ribbed as well as non-ribbed ducts. Moreover, effects that ribs impose on pattern shapes and alterations that patterns undertake as consequences of change in ribs geometrical dimension were studied. In additions to study the effect of pitch on flow patterns, three different pitches were implemented to justify generality of the acquired data. As shown in Table 1, this is the first study on examinations of ribs pitch and thickness effect in horizontal rectangular ducts in open literature.

2. Experimental setup

In brief, to describe the experimental apparatus used to conduct the present study, it is convenient to divide it into three specific sections namely water supply loop, air supply loop and test section.

The complete experimental setup is shown in Fig. 1. Closed water loop consists of two specific circuits. The first circuit, which