TWO-PHASE FLOW IN COILED FLOW INVERTER

By

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Two phase flow (2) coil flow inverter

CERTIFICATE

This is to certify that the thesis entitled, ***'Two-Phase Flow in Coiled Flow Inverter'*** being submitted by **Ms Subhashini Vashisth nee Ghorai** to the Indian Institute of Technology, Delhi for award of Doctor of Philosophy is a record of bonafide research work carried out by her under my guidance and supervision in conformity with the rules and regulations of Indian Institute of Technology, Delhi.

The research report and results presented in this thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

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... See I made it Happen

Dedicated to

... My Dearest Parents

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Subhashini Vashisth

Abstract

Introduction

The need for energy saving and eco-friendly processes which are substantially compact and give higher efficiency have led to the concept of Process Intensification (PI). For the last 10 years, industry has been facing the challenges to reduce the energy demands by increasing the process efficiency and at the same time maintaining the environmental norms. It focuses on the miniaturization of unit operations to accomplish reduction in energy use, capital expenditures, plant profile (height) and plant footprint (areas) while sustaining to the environmental regulations and safety consideration. Coiled tubes have added advantage over the conventional straight tubes in terms of enhanced heat and mass transfer coefficient, flatter velocity profiles, narrower residence time distribution and compactness. Coiled tubes such as helical and spiral coils find a wide variety of application as inline mixers, heat exchangers, chemical reactors, heat recovery processes, air conditioning and refrigeration systems, food and dairy processes, oil pipeline systems, steam generators, thermosyphons, nuclear reactors and other process equipments.

Coiled flow inverter (CFI) is one such innovative device, which has potential for the intensification of processes currently carried out in conventional motionless mixers and coiled tubes. This innovative geometry utilizes the benefits of centrifugal force and complete flow inversion to its advantage. CFI configuration consists of equally spaced coils with alternate 90^{o} bends in between. At the end of each bend, the velocity field is rotated by 90^{o} before entering the next bend. This phenomenon increases the radial mixing, which improves its performance as compared to straight tube and coiled tubes. It

has two-fold advantage of intensifying the convective transfer processes (i.e. increase heat and mass transfer coefficients) and also provide increased transfer area per unit volume of space. It is very compact in size as compared to straight tubes and coiled tubes. Hence it is a step towards innovation of a device for process intensification.

Objective

Flow Regime Mapping, Pressure Drop, Void Fraction and in Coiled Flow Inverter

Experimental investigations on pressure drop, void fraction and flow regime mapping was carried out for gas-liquid two-phase flow system in Coiled Flow Inverter. The coils were prepared using a tube of internal diameter 0.005 - 0.015 m, curvature ratio (coil diameter/tube diameter) varying from 6.7 – 20, dimensionless pitch from 0.0318 to 0.0796 and number of bends from 1 – 15. Liquid flow rate was varied from 3.33 x 10^{-6} to 0.001 m^3/s and the gas flow rate was changed from 8.33 x 10^{-5} to 0.001 m^3/s. Sixteen CFI(s) of different geometric configurations were tested.

Various flow patterns observed were stratified, slug, plug, wavy and churn flow. Data from 7582 gas-liquid flow experiments in Coiled Flow Inverter have been processed for power law and composite power law friction factor correlations for flow regime determination. An empirical correlation for void fraction for laminar, transition and turbulent regimes were developed. The results were compared with Lockhart-Martinelli correlation and Hughmark's correlation.

Comparison of two-phase friction factor with that of different geometries such as straight tube and coiled tube for single and two-phase system was made in order to account for

the increment in pressure drop. It was observed that, due to the effect of secondary flow and flow inversion, the two-phase frictional pressure drop in these types of flow inverters is higher than that of a coiled tubes and straight tube by a factor of nearly 2.5 to 3 folds respectively. The experimental data obtained for different CFI geometries were compared with the published works on coiled tubes. Empirical correlation for two-phase friction factor in CFI was developed. The proposed correlation separately accounts for the effect of curvature ratio, number of bends, gas and liquid flow rates and also retains the identity of each phase. It was found to fit the experimental data within ± 15 % and can effectively predict the friction factor for coiled tubes as well.

Liquid-Phase Residence Time Distribution (RTD) in Coiled Flow Inverter

Mixing performance of CFI for two-phase flow system was explored by carrying out liquid-phase residence time distribution (RTD) for gas-liquid co-current flow. The step response experiments were carried out under the conditions of both negligible and significant molecular diffusion using gas-Newtonian and gas-Non-Newtonian fluids. Reduction in axial dispersion in CFI occurs due to secondary flow and flow inversion with increase in Dean number and number of bends. It is interesting to note that under identical process conditions the reduction in dispersion number is nearly 2.6 times for two-phase flow in CFI with 15 number of bends as compared to a coiled tubes. A modified axial dispersion model has been proposed to describe the liquid phase RTD through CFI. In order to characterize the efficiency of the device, a criterion is proposed that takes into account both the mixing characteristics and pressure drop in CFI.

Superiority of the proposed device has been established on the basis of its performance substantially closer to ideal plug flow, low initial and operating costs, compactness and ease of fabrication.

Modeling of Two-Phase Flow in Coiled Tubes and Coiled Flow Inverter Using Computational Fluid Dynamics (CFD)

Rigorous two-phase flow modeling is one of the great challenges in the classical sciences. Several issues regarding the development of velocity fields, local and average friction factor, phase distribution and entry length in two-phase flow in complex geometries still remains open. Extensive literature survey shows that very limited efforts have been made in past to understand the fluid mechanics of such flows in coiled tubes. Two-phase CFD calculations, using Eulerian –Eulerian model and commercial CFD package FLUENT 6.3, were employed to calculate the gas-liquid flow in straight tubes, coiled tubes and CFI. The present work attempts to examine and understand the effect of the geometrical parameters (curvature ratio, λ (= D_c/d), dimensionless pitch, H) and operating conditions, Dean number ($N_{De} = N_{Re} (1/\lambda)^{1/2}$) on the hydrodynamics of stratified two-phase air-water flow in coiled tubes. The major issues discussed were concerned with the effect of coiled geometry on the evolution of flow field and the associated wall shear. It has been demonstrated that the curvature in coiled geometry may cause a substantial asymmetry in the radial distribution of the main flow velocity. This, in turn, leads to a significant, non-uniform increase in the wall shear stress. Another important issue considered was the effect of the length of the curved section required for fully developed flow. If the coiled tube is sufficiently long, the asymmetric velocity profile eventually reaches a fully developed pattern. The effect of non-dimensional flow parameters, the Reynolds and Dean numbers, on the entry length along the coiled geometry was also investigated in this paper. It was observed that the distribution of local friction factor was smooth near the inlet and as the flow proceeds the difference of local friction factor between the maximum and minimum increases. It was seen that pitch decreases the magnitude of average friction factor. As λ increases, the friction factor decreases due to the decrease in curvature effects. The length to achieve fully developed flow for both single and two-phase flow increases with increasing Dean number. A correlation was also developed to determine the entry length of flow in coiled tubes.

Concluding Remarks

The superiority of Coiled Flow Inverter over any other mechanical device for inducing mixing in flow reactors can be judged by its performance substantially closer to plug flow lower pumping cost, compactness and ease of fabrication. Experimental and numerical investigation on two-phase flow studies carried out in CFI to study its performance establishes it as an effective and economical alternative to conventional straight tubes and coiled tubes. A mixing criterion, C_{mix} is proposed that takes into account both the mixing characteristics and pressure drop in CFI. The enhancement in mixing performance was nearly 3.5 times for Coiled Flow Inverter with 15 number of bends than that of a coiled tubes. CFI has enormous potential areas of application such as inline mixers for liquid–liquid and gas–liquid systems, reactors, heat exchangers, biosensors and membranes.

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