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The control and maintenance of desired flow patterns in bends of different orientations

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ABSTRACT

Multiphase flows are common in industrial settings and bends in pipe lines cannot be avoided due to space limitations. Gas-liquid two phase flows could form material discontinuities that could have adverse effect on productivity and the pipe network due to sudden variations resulting due to the rapid momentum flux variations at fittings such as bends. Research into gas-liquid flow and bends can be motivated by the effect of the bend on the flow downstream of it which could alter the flow pattern occurring and the performance of downstream equipment. Alternatively, the interest might come from what occurs in the bend itself, there could be dryout of the film on the walls and consequent damage to the heat transfer equipment. Here we present measurements made with a number of accurate and fast responding sensors on three cases, two on the effect of the bend and one considering effects in the bend. The results show that the flow transformations occur in two phase flows depending on the orientation of the bend and the change could be captured using fast sweeping measurement techniques. We present the evidence of effectiveness of several types of measurement techniques that could fit into various combinations of phases. The results, point to how to achieve certain flow patterns. Also recommendations are provided regarding the position of any sensor installed to determine flow pattern.

1. Introduction

Gas-liquid flow occurs in a variety of industries in many pieces of equipment and the linking pipework between them as well as in the environment. Of the diverse geometries through which gas-liquid flows pass, bends are an almost overlooked component. Yet they are central to some equipment such as fired reboilers. It is also noted that volcanic conduits can include changes of direction, i.e., bends [1].

Now, bends, in many applications are just used to change the direction of a flow. However, it is important to understand the parameters required to define a bend. The first three parameters are the pipe diameter and the angle and radius of the bend. The angle of the bend, the angle between the inlet and outlet pipes, is most usually 90° or 180°. Because it is gas-liquid flow that is being considered where gravity can cause stratification, the orientation of the inlet and outlet pipes must also be considered. It will be shown below that there are significant differences in going from horizontal to vertical and from vertical to horizontal. Finally there is the orientation of the bend. In the case of a 180° bend with both inlet and outlet pipes horizontal, whether the two pipes are in the same horizontal plane or whether the inlet or outlet pipe is on top can cause very noticeable difference to the flow as shown by Sakamoto et al. [2].

Control of the processes which affect the behaviour of gas-liquid flows in bends and its consequences can be passive or active. The former can involve activities such as design prior to construction or via modifications. Active controls demands continuous measurement of relevant variables and adjustments of flow rates or other parameters. Obviously, there is strong need for detailed knowledge of the distribution of the phases about the bend. This paper considers such information, that in the literature and particularly that generated by the authors of this paper. The implications for control will be discussed using two examples: (i) a fired reboiler with serpentine tubing and (ii) a novel combined bend/T-junction phase separator.

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An extensive review of the available data on gas-liquid flow in bends is given by Azzopardi [3] which covers information available to that date. The effect of U and inverted U bends has been considered by Golan and Stenning [4] and Takemura et al. [5] who noted that they act as phase separators because of the combined effect of centrifugal forces and gravity. In a U bend the two forces act in the same direction, usually sending the liquid to the outside of the bend and gas to the inside. In the inverted U-bend case the forces can act in opposite directions at lower liquid flow rates. However, at higher liquid flow rates, the centrifugal forces dominate and the liquid goes to the outside of the bend. Takemura et al. [5] confirm these trends from wall temperature excursions in electrically heated experiments. Golan and Stenning [4] report that the effect of the bend on phase distribution disappeared by 10 pipe diameters downstream of the end of the bend for the inverted U-bend case and 4 pipe diameter for the U-bend.

Fired reboilers are often used in refineries and other hydrocarbon processing plants to provide vapour where the boiling point of the hydrocarbon liquid is too high for steam to be used for heating. The tubing, usually of 0.1–0.15 m internal diameter, is fitted around the sides of the cylindrical or rectangular fire box. The flow is divided into several streams in parallel and each of these passes through an up and down serpentine arrangement. A major problem that can affect these units is "coking". Dry-out of the wall film in annular or churn flow in the tubes can result in a local increase of wall temperature which can lead to a breakdown of the higher molecular weight hydrocarbon and deposition of carbon, in the form of coke, on the walls. If not detected this can build up and block the pipes. It tends to occur at lower mass flow rates. Indeed, a rule of thumb in the design of these units is that the mass flux through each tube should be at least 1000 kg/m^2 s. Chong et al. [6] developed a model for these units based on the annular flow model of Hewitt and Govan [7] which took into account entrainment of liquid from the wall film and its redeposition back on to the film. For the serpentine geometry Chong et al. added the simplifying assumption that, at each U and inverted U bend, the drops entrained in the gas flow were deposited on to the film. This gave conditions at which the film dried out, which was usually just before a bend, and showed that the flow rate at which dryout occurs increases with increasing heat flux. For heat fluxes usually employed, the value 1000 kg/m^2 s was a conservative value. However, the calculations pointed out that if there was maldistribution between the parallel flow paths, those with lower flow rates could suffer dryout and, hence, coking. Industry sometimes uses a simple practical solution to prevent coking. The length of pipe just before the bend where dryout is most likely is insulated thus lowering the possibility of dryout.

Single or combinations of T-junctions, with one inlet and several outlets have been given serious consideration for use as gas-liquid phase separators. Azzopardi et al. [8] give details of a *partial* phase separator based on a bend/T-junction combination which was installed in a hydrocarbon processing plant and operated successfully until the plant shut down. It has been suggested that better positioning of the phases approaching the junction would improve separation efficiency. Sanchez-Silva et al. [9] have endeavoured to do this by positioning a branch pipe on the outside of a 90° bend with inlet and outlet pipes placed horizontally. They studied the effect of gas and liquid flow rate and the angle of inclination on the phase separation for slug flow approaching the bend. Increasing both gas and liquid flow rates increased the fraction of liquid taken off through the side arm. Baker et al. [10,11] used control of a valve on one of the outlet lines of a multiple T-junction separator to optimise the efficiency of phase separation. They determined that different valve settings were required for this optimum separation and used an ECT system to identify the flow pattern.

Therefore, the knowledge of the flow phenomena in bends and their effect on downstream flow patterns is very important to many industrial applications involving multiphase flow. The flow distribution is affected by many factors such as the physical properties and velocities of fluids, the geometry (diameter, angle and curvature) and orientation of the bends. This paper is aimed to provide a more complete understanding on the effect on the flow after the bends (effect of bend) and on the flow behaviour occurring in bends (effect in bend) through comprehensive experimental investigation employed advanced instrumentations. The experiments were conducted using air as gas phase and tap water or silicone oil (5 m Pa s viscosity) as liquid phase. Bends with different geometries and orientations were examined. The work aims at providing useful data for the control and maintenance of desired flow patterns in and downstream of bends.

2. Review of previous work

Anderson and Hills [12], reported data on liquid film thickness, axial pressure profiles, gas velocity distribution, and droplet entrainment in the annular flow regimes in a vertical inverted 180° return bend. The diameter and radius of curvature of the bend are 25 and 305 mm, respectively. They reported that an increase in film thickness on the inside of the bend can be attributed to the action of gravity and to the secondary flow existing in the gas phase. A change in flow pattern from annular to stratified flow in the bend at low liquid flow rates was observed. On the other hand, for the high liquid flow rates, a local maximum in the film thickness was seen on the inside and outside of the bend.

The distributions of water films and entrained droplets in air–water annular flows in 180° horizontal bend were investigated by Balfour and Pearce [13] using sampling probes. The diameter and radius of curvature of the bend are 25 and 48.5 mm, respectively. They took a series of measurements with the probes positioned at 45° intervals around the tube exit and at varying radii. They concluded that in those annular flows where the air speed is high, many of the entrained droplets are thrown very rapidly to the wall and that the entrained fraction tends to be negligible for high quality annular flows where the films are thin.

Using needle probes to measure the local void fraction around an inverted U-bend attached to a 50.8 mm internal diameter pipe in the case of froth flow enabled Hoang and Davis [14] to determine the slip ratio, which was found to be greatly increased at the bend exit, relative to the entry, for low velocity conditions. These values diminished slightly in the downstream flow pipe. Later, Takemura et al. [5] presented experimental results on the flow behaviour, pressure drop characteristics and dryout characteristics from the Joule heating of gas-water two-phase flows through U-shaped and inverted U-shaped bends, each having an internal diameter of 18 mm. They compared the results obtained from both bends and concluded that for the U-shaped bends, the gas phase flows along the inside of the bend, regardless of the flow rates of gas and water. Whilst in an inverted U-shaped bends, at lower gas and liquid flow rates, the tube wall at the outside of the bend at the angles of 150–180° around the bend is in contact with the gas phase. They also reported that the inverted U-shaped bends have a wider safety region against dryout than the U-shaped bends.

Tingkuan et al. [15] studied the flow patterns in a vertical 180° bend using visual observation and physical measurements using electrical conductance probes. The diameter and radius of curvature of the bend are 21.5 and 305 mm, respectively. They compared their transition data to those reported by Mandhane et al. [16] and Weisman et al. [17]. They concluded that their data fitted the transition criteria from both sources well and that the major