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A simple flow device for enhanced mass transfer in reduced dimensions

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HIGHLIGHTS

- 90° bend promotes slugging in two phase flow.
- This phenomenon significantly improves mass transfer characteristics.
- Multiple bend has higher mass transfer rates than a single bend and helical coil.
- Addition of multiple bends enhances transport process at the cost of pressure drop.
- Multiple bends in series is a PI device for method aseptic bio-processes.

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ABSTRACT

The present study proposes a device for process intensification for liquid–liquid flow systems in millimeter size conduits. This is accomplished by incorporating a 90° bend such that the flow is initially horizontal and then in downward direction. The device intensifies mass transfer controlled processes by enhancing the range of Taylor regime and decreasing the range of parallel flow, both contributing positively to enhanced mass transfer as compared to straight conduits. The proposed device has been numbered up by incorporating multiple bends connecting short horizontal sections to vertical up and downflow sections. This system is noted to be more effective than a helical coil which is a commonly used process intensification device in practical applications. The effectiveness has been quantified by considering the (a) overall volumetric mass transfer coefficient, (b) extraction efficiency and (c) energy dissipation parameter.

1. Introduction

Process intensification is an engineering expression that refers to making changes that render an altered manufacturing or processing design substantially improved in terms of energy efficiency, cost-effectiveness or enhancement of other qualities alone, or in combination. The concept is intimately related to the physical nature of the plant and is not something which will take a long time to move from theory to final commercial application using existing and available hardware. It not only includes options of improving existing technologies but also incorporates development of new technology. Micro-reactor technology today represents attempts for process intensification at its extreme. This concept was first introduced by Ramshaw [22] who defined it as "a design strategy to make dramatic changes in plant sizes by several orders of magnitude". Several process intensification techniques proposed for enhanced transport characteristics attempt to optimize capital, energy, environmental and safety benefits. These include use of passive mixers which is already established for large diameters conduits [1], miniaturised devices (micro and milli) for enhancing the surface area available for mass transfer [2–6], use of ultrasound and vibration for inducing high mass transfer rates [7–13] and use of supercritical solvents [14–15]. There are also, several other options that are not mentioned here.

The present study employs the phenomenon of "bend induced slugging" to effect process intensification in a 2 mm conduit. The device aims to enhance transport characteristics and reaction yield by modifying the flow characteristics of two phase systems and is based on the technical know-how gathered till date on the hydrodynamics of gas–liquid and liquid–liquid flows. It also ensures improved contacting without intense turbulence, which is particularly important for aerobic fermentation and other biochemical reactions where bacterial cells suffer death under severe physical/mechanical stress. Since the device does not use any moving parts or external energy input, it ensures aseptic mode of operation

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particularly useful for bioreactors. The "multi bend device" is noted to be more effective than a helical coil of same total length both in terms of mass transfer and pressure drop.

1.1. Rationale behind the design

A survey of the past literature [3,16] and experiments by the present authors [17] suggests that miniaturization brings about process intensification since it is accompanied by an increased parametric range of slug flow [3,16]. Slug flow enhances mass transfer characteristics due to the coupled effect of internal circulation due to convection within each slugs and diffusion between slugs of adjacent phases [3]. From this, one can infer that any technique which promotes slug flow is expected to serve as a process intensification method. Multiphase flow literature [18–20] reveals that gas–liquid flow through risers following a bend enhances slugging. This is normally an undesirable phenomenon in oil industries as it leads to rapid fluctuations in flow and pressure. Based on the aforementioned observations, we felt intuitively that "bend induced slugging" can be used to our advantage for enhancing heat/mass transport. Accordingly, the study proposes a compact device comprising of a manifold of 90° bends connecting short horizontal and long vertical up and downflow sections. We also note [17] a significant effect of orientation on mass transfer co-efficient during liquid–liquid flow in straight conduits – the highest mass transfer occurs during downflow and the least during horizontal flow of the two liquids. Accordingly, the device is oriented to ensure a greater proportion of downflow with a minimum proportion of horizontal flow. The improvement in mass transfer over the same device oriented to ensure a greater proportion of upflow has also been discussed.

2. Experimentation

2.1. The device and its novelty

The device (Device 1 in Fig. 1) provides changes in flow direction via four 90° bends in a conduit of 2 mm internal diameter. It is oriented to ensure greater proportion of downflow length (downflow/upflow = 2, downflow/horizontal = 4.66) for a total length (0.8 m) of the flow passage. The dimensions of the individual sections as specified in the figure are selected considering ease of fabrication and maintenance with the present infrastructural facilities.

The proposed device has the following advantages over the devices employed conventionally for enhancement of transport processes:

- Since the device ensures the required process intensification by only geometric modification (introduction of bends) of the channel, no external energy input and no special devices like low frequency oscillation/pulsation or mixing devices like magnet or passive mixers are required for heat and mass transfer enhancement.
- Aseptic mode of operation is possible which is particularly useful for biological applications.
- The system can be scaled up simply by numbering up approach which implies using systems in parallel, suitably packaged in a single unit. This also ensures that the non-functional units can be isolated easily without affecting the continuous operation.
- Although the same effect can be obtained by liquid–liquid slug flow in microchannels, the fabrication of microchannels is difficult and costly whereas our system is low cost and can be easily fabricated.
- Our system will be effective for fluids widely differing in viscosity and surface tension which in general are difficult to mix.
- The device is cheap and easy to construct and operate.

2.2. Testing of the device/ experimentation to test the device

The device has been evaluated for a mass transfer controlled non reacting system to understand the influence of hydrodynamics on transport characteristics. The results reported here are for a liquid–liquid flow system - the two liquids being toluene mixed with 10% acetic acid by volume and water. After flowing through the test rig, the liquids are collected in a separator tank, gravity separated and subsequently recirculated through the recirculating system. This system comprises of two pumps and four flowmeters to circulate measured flows (Q_W and Q_T) of the liquids through the test sections. The details of the flow arrangement is discussed and presented in Biswas et al. [17].

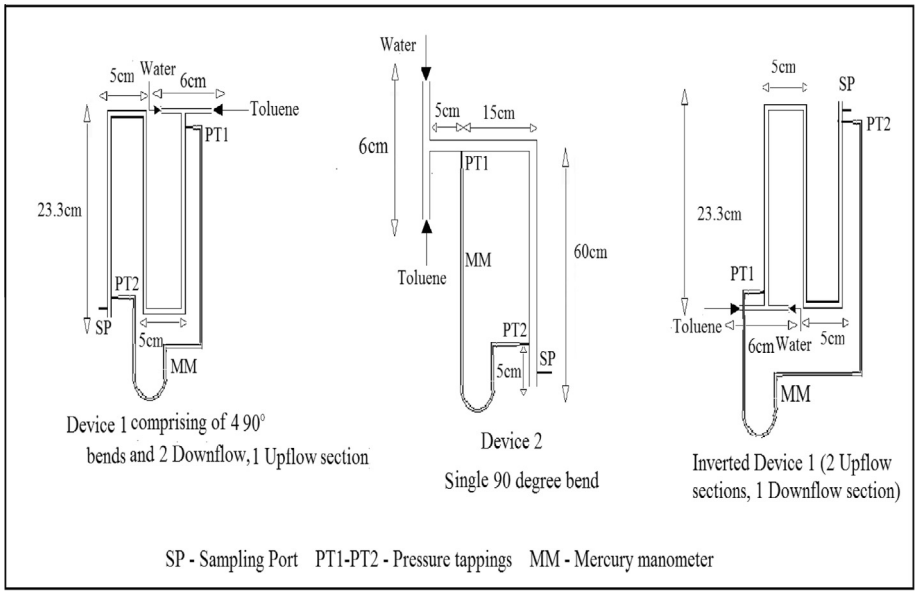

Fig. 1. Schematic of the test sections.