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Research Paper

Effect of the bend geometry on the two-phase frictional pressure drop and flow behaviour in the vicinity of the bend

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HIGHLIGHTS

- Two-phase pressure drop in the vicinity of a sharp return bend is investigated.
- Four different bend geometries tested in upward- and downward oriented flow.
- Capacitance time traces used to assess bend effect on two-phase flow.
- Void fraction and wave activity are derived from capacitance signal.
- Correlation between observed flow behaviour and the observed pressure drop.

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ABSTRACT

The effect of a sharp return bend on the two-phase flow frictional pressure drop close up-and downstream of the bend is investigated. The measurements are performed for refrigerant R134a at mass fluxes ranging from 200 to 500 kg/m^2 s. Four bend geometries are tested, with inner channel diameters ranging from 4.93 mm to 8.1 mm and the curvature ratio between 2.55 and 4.43. For both up-and downward oriented flow the main bend effect on the frictional pressure drop is observed close downstream of the return bend. However, for downward oriented flow a decrease in pressure drop is observed and for upward flow an increase is found. To assess the effect the underlying flow behaviour, the void fraction time trace is analysed. The average void fraction and wavelet variance of the void fraction signal can be used to explain the trends in the frictional pressure drop. The correlation between the frictional pressure drop and the flow behaviour indicators is investigated quantitatively for the different geometries.

1. Two-phase flow behaviour and pressure drop in the vicinity of a sharp return bend

This work is focussed on compact fin-and-tube heat exchangers, these units are frequently found in residential applications such as heat pumps and air conditioners [1]. The compactness of these units is attained by folding the tubes up into a sequence of short straight sections and sharp bends. To reach a good performance of the unit, it is important to gain insight on how the geometry of these tubes influences the performance [2–4]. If these heat exchangers are used as condenser or evaporator, the two-phase flow will be affected by the channel/bend geometry [5,6]. Furthermore, due to the strong link between the two-phase flow behaviour and the frictional pressure drop and heat transfer [7,8], the specific shape of the channel can influence the performance of the unit. Given this considerations, it is necessary to evaluate the effect of the bends in the channel on the flow behaviour to gain insight in the frictional pressure drop occurring in the channel.

Some work can already be found in literature on two-phase frictional pressure drop in and in the vicinity of a sharp return bend [4,9–12]. Most of the research concerning the effect of bends on two-phase flow pressure drop is focused on the bend section itself, however, there are studies which show that the bend can have a significant effect on the pressure drop upstream and downstream of the bend [13]. Furthermore, in most research the underlying flow behaviour is ignored [10,11] and in cases where the flow behaviour is investigated to gain insight in the frictional pressure drop, this is done through flow visualizations [4,9,12]. These flow visualizations offer a good qualitative image [14]. However, manual processing of this material to assess the intensity and extent of the flow disturbance is very subjective.

De Kerpel et al. [13] studied the pressure drop close up- and downstream of a sharp return bend. The working fluid under

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Nomenclature

D	diameter (m)
F	frequency (Hz)
G	mass flux (kg/m^2 s)
ID	inner diameter (m)
OD	outer diameter (m)
p	probability of no correlation (–)
R	bend radius (m)
S	ratio of a value to its reference (–)
T	temperature (K)
U	velocity ratio (–)
V	velocity (m/s)
x	vapour quality (–)
$\Delta P_{\text{frictional}}$	frictional pressure drop (Pa)
$\Delta P_{\text{momentum}}$	momentum pressure drop (Pa)
ΔP_{static}	static pressure drop (Pa)
r_s	spearman rank correlation coefficient (–)
r_p	pearson correlation coefficient (–)

Greek symbols

α	average (–)
ε	void fraction (–)
ν	wavelet variance (–)
ρ	density (kg/m^3)

Subscripts

L	liquid phase
V	vapour phase
frict	frictional
REF	reference value

consideration was R134a, which is a dielectic. In order to study the underlying two-phase flow behaviour the capacitance of the flow was measured at several locations up-and downstream of the return bend. The capacitance trace is an indication of the flow behaviour; due to the difference in dielectric constant of the phases the capacitance will be affected by the amount of each phase present [15]. This capacitance trace can be converted to a void fraction signal through a flow regime based calibration [15,16]. De Kerpel et al. [13] reduced this void fraction signal to two flow behaviour indicators: the time-averaged void fraction, indicating the average flow behaviour and the wavelet variance of the void fraction signal, indicating the main scales (frequency content) of the flow behaviour. These flow behaviour indicators were then used to explain the trends observed in the two-phase frictional pressure drop. This was done for only one bend geometry, with a radius of 10.2 mm and an internal channel diameter of 8.1 mm, for both up-and downward oriented flow. Furthermore the link between the frictional pressure drop and the flow behaviour indicators is made on an intuitive basis. In this work, the two phase flow frictional pressure drop and capacitance of the flow is measured in the vicinity of multiple bend geometries, in order to assess the bend effect for multiple bend geometries. Furthermore, the link between the flow behaviour indicators (time-averaged void fraction and wavelet variance) and the frictional pressure drop is investigated more quantitatively with correlation coefficients.

2. Experimental setup

The experiments are performed on a test setup designed to generate a two-phase flow at a certain temperature, vapour quality x and a mass flux G. The refrigerant used is R134a. For mass fluxes lower than 250 kg/m^2 s, the relative uncertainty on the mass flow rate is smaller than 1.5% and at mass fluxes higher than 250 kg/m^2 s the relative uncertainty is smaller than 0.75%. For the vapour quality x, the absolute uncertainty varied between ±0.005 and ±0.02, with higher values occurring at higher vapour qualities. The saturation temperature at the inlet of the test section was controlled to within ±0.5 °C.

For the sake of simplicity, the main test setup will not be discussed here. The discussion of the main test setup can be found in De Kerpel et al. [13,17].

Two test sections are added to the main test facility (Sections 2.1 and 2.2) to allow for evaluation of the two-phase flow behaviour and the pressure drop in the vicinity of a sharp 180° bend. The flow behaviour is assessed based on the trace of the electric capacitance of the flow. Due to the construction of the capacitance sensor, the pressure drop and capacitance cannot be measured in the same test section. Five different bend geometries are tested, these are summarized in Table 1. This work mainly focusses on small tube diameters and sharp return bends (small curvature ratio 2R/D). The tested bend diameters and curvature radii are in the range of tube diameters and curvature radii used in compact fin-and-tube heat exchangers for domestic heat pumps.

2.1. Test section for capacitance measurements

In this work, the capacitance trace of the flow is used to assess the flow behaviour in the vicinity of a sharp return bend as proposed by De Kerpel et al. [13,17]. The capacitance is measured at several distances from the return bend (Fig. 1 and Table 2). At these locations capacitance sensors based on the design by Canière et al. [18] are placed. The core of these capacitance sensors is a pair of sensing electrodes, these electrodes have an axial length of 1D, i.e. this is 8 mm for Geometry 1–3 and 4.83 mm for Geometry 4. These electrodes are concave, each covering the tube over 160° leaving just 10° of bare tube wall at the top and bottom of the tube.

The capacitance between the electrodes is measured using a transducer which was made in-house. The transducer design is based on the one proposed by Yang and Yang [19]. The output of the transducer is a voltage between 0 and 10 V. The sensitivity of the transducer is 1.16 V/pF and the output accuracy is 4 mV. The capacitance difference between full vapour flow and full liquid flow is dependent on the refrigerant used. For R134a this difference is 1.05 pF. The voltage is logged with a DAQ system. For each measurement the capacitance time trace is acquired for 5 s at a sample frequency of 2 kHz.

2.2. Test section for pressure drop measurements

The test sections for the pressure drop measurements are essentially made out of a single length of tube of about 4 m. In

Table 1
Tested bend geometries for both the test section for capacitance measurements and the test section for pressure drop measurements.

	OD (mm)	*ID* (mm)	*R* (mm)	2*R*/*ID* (–)
Geometry 1	9.53	8.1	10.2	2.55
Geometry 2	9.53	8.1	12.7	3.13
Geometry 3	9.53	8.1	16	3.95
Geometry 4	6.35	4.93	10.9	4.43