Influence of Surface Roughness on Pressure Drop in Two-Phase Flow of Saturated Hydrocarbons

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Pressure drop of propane and propylene in gas-liquid saturation state are investigated for copper and mild steel test tubes. The surface structure of both tubes is determined with the focus variation method, yielding a six times higher roughness for the steel tube, although both tubes are manufactured in the same manner. In both tubes single phase pressure drop validation measurements are carried out and compared to known correlations. For two-phase investigations both fluids are investigated at the reduced saturation pressure for three different mass fluxes. The vapor quality is varied.

1 Introduction

Two-phase flow of gas and liquid is a widely investigated topic due to the complexity of interaction between both phases, which complicates analytical treatment. Since pressure drop is an important issue in process engineering, many empirical correlations are published in literature to determine pressure loss. There are contradicting statements regarding the influence of the surface roughness, although the impact on single-phase flow is common knowledge. Friedel [1] and Müller-Steinhagen and Heck [2], who derived their correlations based on a two-phase multiplier model and experimental data, do not consider the influence of roughness in their respective correlations, whereas Theising [3] and Kind [4] do so. However, there is a lack of experimental research in literature regarding pressure drop with different tube surface roughnesses and an in-depth analysis of these surfaces.

2 Experimental Procedure

The experimental apparatus, which is described in detail in [5,6], is shown in Fig. 1. A multiphase pump conveys a two-phase saturated test fluid, which is separated in its liquid and vapor component in a phase separator due to buoyancy. The mass flow of each phase is adjusted by several regulation valves and Coriolis mass flow meter. The desired vapor quality and mass flux are obtained by mixing both phases in a static mixer. Subcooling of the liquid phase in HE 4 and superheating of the vapor phase due to pressure drop in the respective flow line are taken into account for determination of vapor quality. For single-phase measurements, either the vapor or the liquid line are closed off by ball valves.

A copper tube with an internal diameter of 15.00 mm and a mild steel tube with an internal diameter of 14.65 mm are used as test sections and the pressure drop is measured along the entire tube length of 3150 mm. The internal surface roughness of both tubes is determined with the focus variation method [7]. In Fig. 2, the three-dimensional topography as well as a characteristic cross section for each tube are shown. Surface parameters according to DIN EN ISO 4287 [8] are listed in Tabs. 1 and 2. Although manufactured alike, the roughness of the mild steel tube is six times higher as that of the copper tube.

## 3 Validation Measurements Based on Single-Phase Systems

Single-phase pressure drop measurements are carried out for validation with propane and propylene as test substance. The results are shown in Fig. 3 for the friction factor as a function of the Reynolds number. For low Reynolds numbers, the experimental results are in good agreement with the correlation for smooth tubes

$$\zeta = \left(1.8 \log_{10}(Re) - 1.5\right)^{-2} \tag{1}$$

from Konakov [9]. For high Reynolds numbers, only the experimental friction factors from the copper tube are in good agreement with the smooth tube correlation, but the

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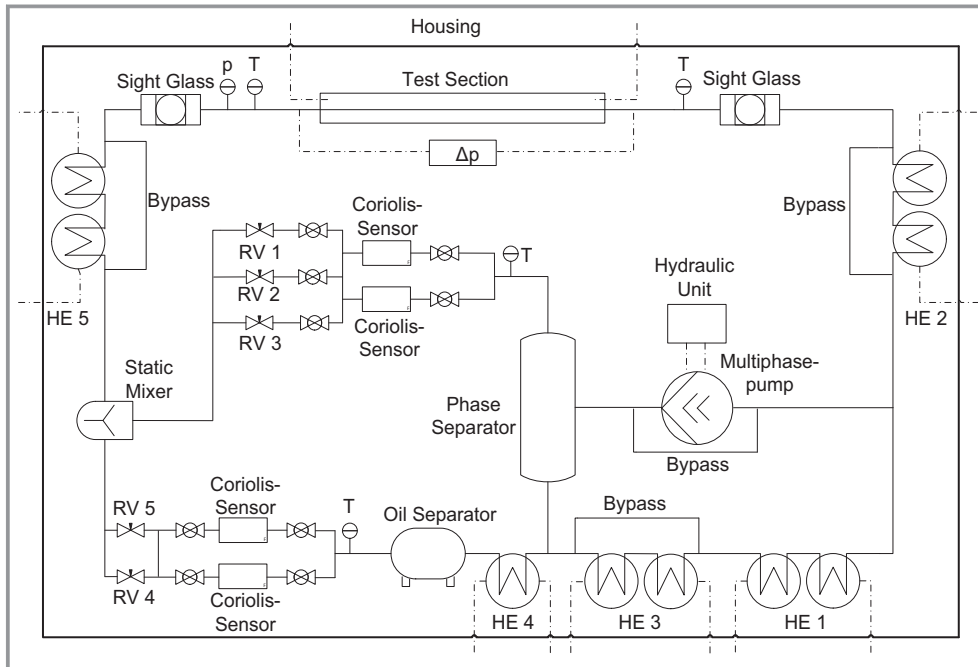
**Figure 1.** Schematic illustration of the experimental apparatus. HE, heat exchanger; RV, regulation valve.
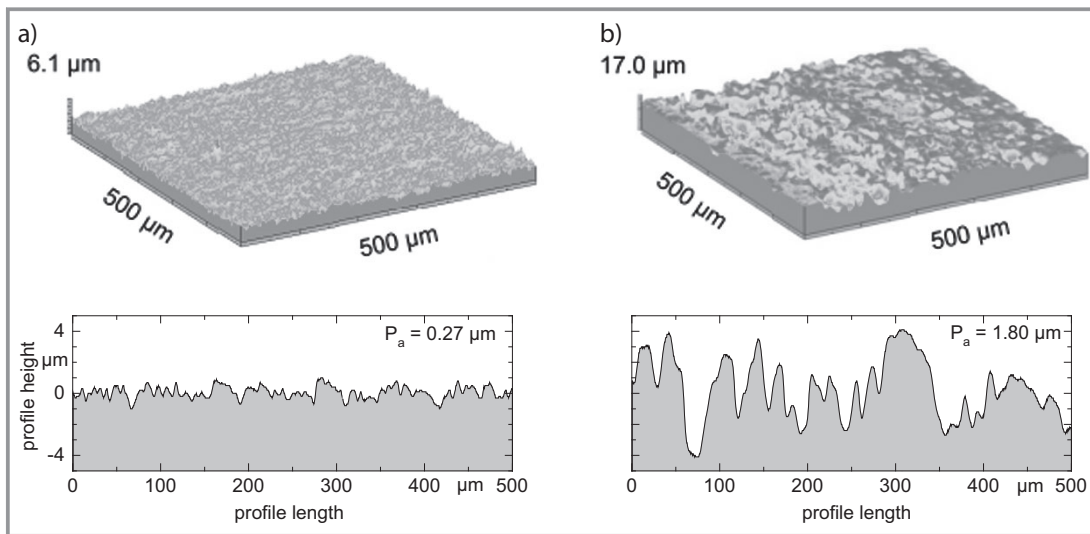
Figure 2. Topographies and profile cuts of a) the copper tube and b) mild steel tube.

Table 1. Surface parameters of the copper tube.

	P_a	P_q	P_p	P_t	P_z
Average	0.27	0.35	0.99	1.97	1.36
Max	0.95	1.22	4.48	9.20	3.57
Min	0.17	0.21	0.42	1.00	0.78
σ	0.06	0.08	0.34	0.53	0.28

Table 2. Surface parameters of the mild steel tube in μm.

	P_a	P_q	P_p	P_t	P_z
Average	1.80	2.27	4.57	11.36	6.99
Max	2.85	3.78	14.47	23.88	14.51
Min	1.09	1.41	2.28	5.75	4.79
σ	0.31	0.40	1.69	2.66	1.13
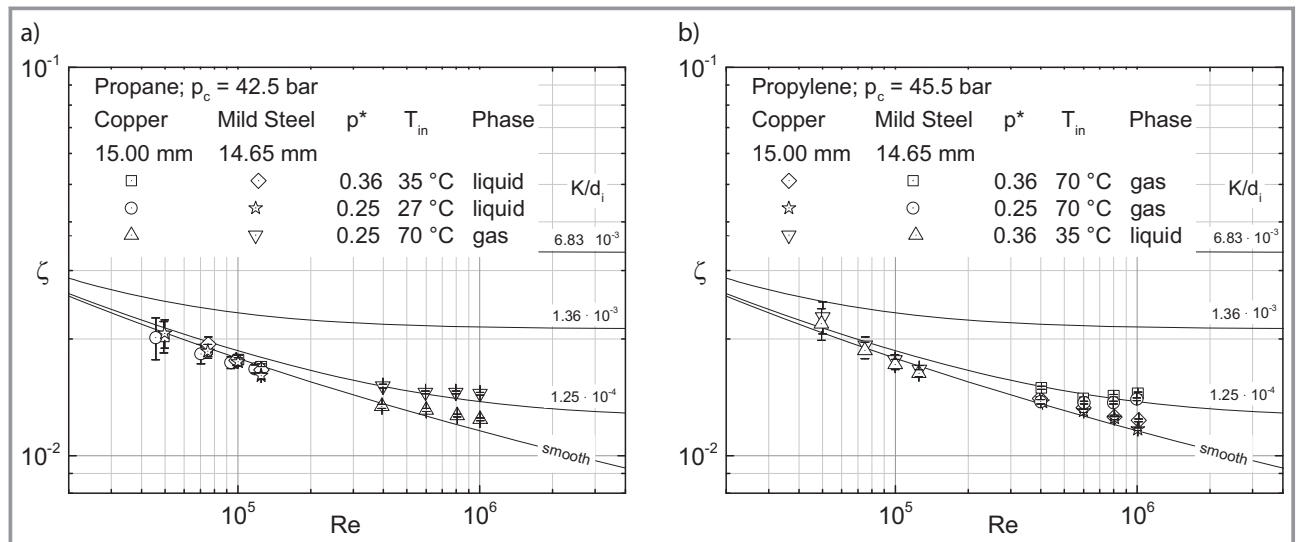
Figure 3. Friction factors as function of Reynolds number for a) propane and b) propylene.

results from the mild steel tube are in average 30 % higher than the prediction of Konakov. This is explained with a disturbance of the laminar boundary layer through the surface roughness (see Schlichting [10]).

The friction factor of rough tubes can be predicted with the implicit method

$$\frac{1}{\sqrt{\zeta}} = -2\log_{10}\left(\frac{2.51}{Re\sqrt{\zeta}} + \frac{1}{3.71}\frac{K}{d_i}\right) \tag{2}$$

from Colebrook [11], with the empirical sand roughness parameter K. However, the values of K range from 0.02 to 0.1 mm according to [12] for mild steel tubes, resulting in relative sand roughness K/d_i from $1.36 \cdot 10^{-3}$ to $6.83 \cdot 10^{-3}$ for the mild steel tube ($d_i = 14.65$ mm) from this investigation. The friction factor according to [11] is calculated for both relative sand roughnesses and shown as a function of the Reynolds number in Fig. 3. Obviously, the friction factor

is highly overpredicted by Colebrook [11], when compared to the experimental results. The overprediction is in the range of 40 %, when the minimum sand roughness is used till 100 % for the maximum sand roughness.

Through regression of the experimental data, a relative sand roughness of $K/d_i = 1.25 \cdot 10^{-4}$ is obtained for the mild steel tube, which is significantly lower than the values suggested by Kast [12]. The absolute sand roughness K is $1.8 \cdot 10^{-3}$ mm, which is 20 % higher than the maximum values for smooth tubes of $1.5 \cdot 10^{-3}$ mm.

4 Discussion of Pressure Drop Results of Two-Phase Flow

In Fig. 4, the pressure drop is shown as a function of the vapor quality and mass flux for propylene with a reduced pressure of 0.25 in the mild steel and the copper tube on the
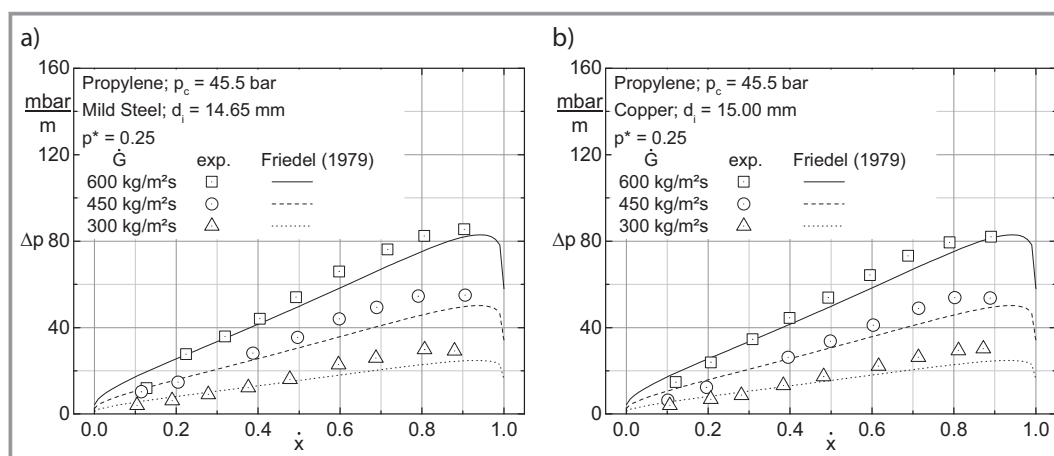
Figure 4. Pressure drop as a function of vapor quality for propylene. a) Mild steel tube, b) copper tube.

left and right side, respectively. Obviously, the pressure drop increases for higher mass fluxes, due to the increased shear stress on the wall and increased turbulence induction. The influence of vapor quality on pressure drop is due to the higher mean velocity of the fluid, because of the lower density of the gaseous phase compared to the liquid. It can also be noted that the pressure drops of propylene and propane (Fig. 5) obtained with the same experimental parameter are quite similar, when compared at the same reduced pressure.

Furthermore, all results are in good agreement with the correlation of Friedel [1] with an average deviation of 20 %, which is inside the uncertainty boundaries of this correlation. However, no influence of the surface roughness is noted on the pressure drop for either propane or propylene, when the results of pressure drop in the copper tube are compared to the results in the mild steel tube.

The hydrodynamics of two-phase flow patterns have to be considered to explain this phenomenon. As known, higher turbulence is generated in single-phase flow when the laminar sublayer is penetrated by the roughness profile. This occurs only for higher Reynolds numbers, when the boundary layer becomes smaller than the maximum height of the surface structure. Hence, turbulences due to wall roughness can only be induced when high flow velocities are achieved. But most important the fast-flowing fluid has to be in contact with the wall.

Wall contact and velocity of both phases are an issue, considering the mentioned two-phase flow patterns. In stratified flow, both phases have the same, rather low velocity, so that a penetration of the sublayer is unlikely. For increasing vapor qualities, however, annular flow occurs where gas velocities are indeed high, but the tube wall is only wetted by the liquid phase. The velocity of the liquid is not sufficient to induce turbulences though. In intermittent flow, the wall is alternately in contact with gas and liquid so that the boundary layer is not in a steady state and penetrated by the fluctuations of both phases, meaning the influence of roughness will be minor. Only in mist flow, a surface

structure influence seems probable, but this flow pattern is not achieved in the current investigation.

5 Conclusions

The experimental procedure is validated with single-phase measurements. The results of the copper tube regarding the friction factor are in good agreement with the smooth tube correlation. The influence of surface roughness of the mild steel is notable on the friction factor with an average increase of 30 % compared to the copper tube for high Reynolds numbers. The influence of surface roughness is overestimated in literature though. Therefore, a more analytic approach needs to be developed to determine the sand roughness parameter K, based on surface parameters such as the envelope method according to Luke [13].

For two-phase flow, no influence of the roughness on the pressure drop is noted. However, more experimental research is necessary to give a scientific concrete statement, since the influence of an internal fin structure inside a tube, e.g., clearly affects pressure drop [14]. Therefore, a boundary layer approach has to be developed to determine the flow conditions, which have to occur, so that the surface structure influences the pressure drop. However, differences to single-phase flow according to [15] have to be considered by that approach, e.g., wetting effects, which are mostly neglectable in single phase flow.]

Symbols used

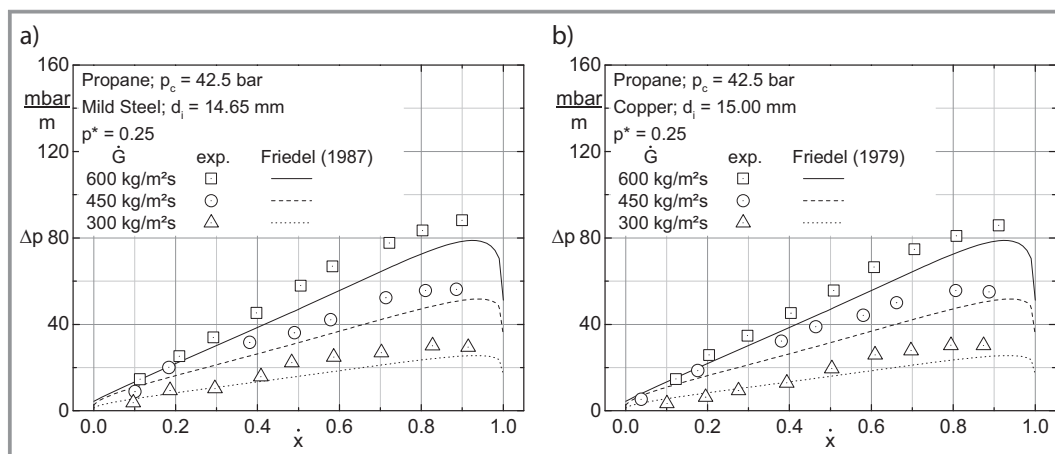|		
d	[mm]	diameter
$\dot{G}$	[kg m^{-2}s^{-1}]	mass flux
K	[mm]	sand roughness
p	[–]	pressure
P	[µm]	roughness parameter according to DIN EN ISO 4287

Figure 5. Pressure drop as a function of vapor quality for propane. a) Mild steel tube, b) copper tube.

Re	[–]	Reynolds number
T	[°C]	temperature
x	[–]	vapor quality

Greek letters

| ζ | [–] | friction factor |
| σ | [–] | standard deviation |

Sub- and superscripts

*	reduced
a	arithmetic mean roughness height
c	critical
i	internal
in	inlet
p	maximum peak height
q	squared mean roughness height
t	total roughness height
z	mean roughness height

Abbreviations

exp	experimental
HE	heat exchanger
Max	maximum
Min	minimum
RV	regulation valve

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