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A Critical Assessment of Two-Phase Flow Distribution in Microchannel Heat Exchangers

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A Critical Assessment of Two-Phase Flow Distribution in Microchannel Heat Exchangers

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ABSTRACT

Due to the many benefits offered by Microchannel Heat Exchangers (MCHX), such as compactness, high heat transfer coefficients, reduced refrigerant charge, and energy and material cost savings, microchannel condensers and evaporators continue to be increasingly applied and investigated in the HVAC&R fields. One of the practical challenges associated with MCHX is the uniform distribution of two-phase refrigerant in the headers and tubes of the heat exchanger. In MCHX, which typically have port sizes about 1 mm or less, to maintain the pressure drop at reasonable levels while providing fairly uniform two phase flow distribution, an appropriate header size and number of tubes need to be chosen.

In this paper, a critical review of experimental and analytical investigations of two-phase flow maldistribution in MCHX is presented. The influence of header and microchannel tube geometry, heat exchanger orientation, flow and operating conditions, fluid properties and flow patterns on the MCHX flow distribution is discussed. Researchers have investigated upward and/or downward two-phase flow in MCHX with horizontal and vertical headers, for which the microchannel tubes/ports are, respectively, vertical and horizontal. Traditionally, compared to investigations in horizontal headers, the studies on vertical headers have been relatively few. However, recently, due to applications involving automotive evaporators, more studies on vertical headers are reported. In all these studies, gravity is seen to profoundly affect the two-phase flow distribution. Various fluids such as R410A, R134a, R245fa, CO_2, air-water, etc. have been studied in published works. Fluid thermophysical properties and flow patterns greatly influence the flow distribution in MCHX. Very few investigators have studied the effects of fluid properties on two-phase flow distribution. Zou and Hrnjak (2014) [16] speculated that fluids with high liquid to vapor density ratio would provide better flow distribution. However, this hypothesis needs to be experimentally confirmed. Most studies agree that in headers, compared to annular flow, churn flow is desirable for better flow distribution. Most of the experimental investigations on flow distribution have been conducted for adiabatic flow. However, the applicability of such investigations to practical situations is dubious as the flow will be accompanied by condensation or boiling heat transfer. Refrigerant mass flux (G) and inlet quality (x) are seen to have a significant impact on flow distribution which is discussed in detail. Tube protrusion into the headers, and tube spacing also greatly affect the flow distribution. Since these interacting factors make the prediction of two-phase flow distribution very complex, a limited number of semi-empirical models/correlations have been proposed to quantify the two-phase flow maldistribution in MCHX. Five correlations for predicting the liquid take-off ratio in MCHX headers were assessed and among these five, Zou and Hrnjak (2013b)[15] correlation for R410A was found to perform reasonably. Based on the current study, recommendations regarding the applicability of these correlations to practical problems have been provided. Having identified and examined the key factors influencing two-phase flow maldistribution in MCHX, recommendations for further study are made.

Keywords: Microchannel heat exchangers, Two-phase flow, Header, Refrigerant, Maldistribution, Take-off ratio

1. INTRODUCTION

Micro channel heat exchangers (MCHX) are heat exchangers in which fluid flows in micro channels having hydraulic diameter typically less than 1 mm. Due to its smaller port size, the processes of heat and mass transfer occurring in the velocity and thermal boundary layers are very effective. MCHXs provide high heat transfer coefficients. Lower internal volume of microchannel tubes help in reducing the amount of refrigerants charged into the system. All the above characteristics mentioned make MCHX more suitable for two phase flow heat exchangers.

Two phase flows are far more complicated compared to single phase flow. Heat transfer and physical properties of the phase cause mass exchange between the phases, by evaporation, flashing and condensation. The effects of surface tension, inertia, viscosity and buoyancy complicates the two phase flow phenomenon.

Flow maldistribution can be induced by the heat exchanger geometry, operating conditions, multiphase flow, etc. In extreme cases, due to flow maldistribution, the fluid doesn't enter some of the tubes which reduces its thermal performance. In evaporators, uniform distribution is essential to avoid dry out phenomena and the resulting poor thermal performance. In condensers, maldistribution of liquid could create zones of reduced heat transfer due to high liquid loading.

Heat exchanger header and tubes can have different configurations. In case of vertical tube configuration, gravity can be seen as the main reason for flow maldistribution. Operating conditions such as mass flux and vapor quality play a vital role in two phase flow distribution in MCHX. These operating conditions can alter flow patterns which provides a way for flow distribution. Refrigerants used in MCHX have different fluid properties. The flow patterns determine the uniformity and non-uniformity of the two phase flow distribution. The churn flow tends to make the flow uniform and uneven distribution is observed when the flow is annular or semi annular.

In this study, a critical review on two phase flow maldistribution in MCHX was done. Factors that contribute towards flow maldistribution such as header/tube geometry, operating conditions (mass flux and vapor quality), refrigerant properties, fluid flow patterns etc. were investigated. Empirical correlations obtained from the papers were analyzed and suggestions to mitigate the severity of flow maldistribution are made.

2. REVIEW OF TWO PHASE FLOW MALDISTRIBUTION IN MCHX:

2.1 Header/Tube Geometry and Configurations

Kim and Sin (2006) [10] investigated the effects of tube protrusion depths (h/D) and tube outlet direction on flow distribution in MCHX. For downward flow, the liquid ratio was higher in the initial channels and the gas flow ratio trend was reverse. When the tubes were protruded, more water were reattached to the rear end of the header with high momentum which helped in better flow distribution. The effect of tube inlet and outlet configurations were studied: Parallel flow and Reverse flow as illustrated in Fig 1.

Fig 1. Different methods of tube inlet/outlet configurations.

The liquid flow distribution was least affected by tube inlet/outlet configuration. The effect of protrusion depth was negligible in case of upward flow. The header length also affected the flow distribution. If the header length was shorter than reattachment length, the separated flow strikes the rear end and supplies liquid from backwards which improves the flow distribution in case of downward flow. Marchitto et al. (2008) [11] conducted experiments inside parallel channels of compact heat exchanger. The diameter of the orifice connecting distributor to channel was significant. When it was reduced, liquid maldistribution was observed while gas maldistribution was reduced and vice-versa. The other geometrical configuration, inlet nozzle at the inlet of the distributor, improved phase distribution into the parallel channels as it provided an increase in flow momentum. The studied also proved that combined use of orifice at the inlet of the vertical channels and the inlet nozzle at the distributor will help in improving the flow distribution. Ahmad et al. (2009) [1] studied about different structural and functional parameters that can influence the flow distribution. Experiments were conducted in three different channel orientations as in fig 2.

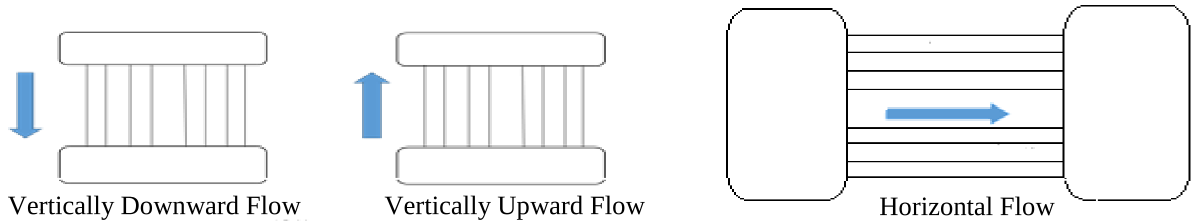


Fig 2. Different Channel Orientations

In case of vertically downward channels, good distribution was observed when the mass quality and velocity were increased. For horizontal orientation, the flow is more uniform even for lower qualities. In case of vertically upward configuration, the flow was mal-distributed for higher vapor quality and higher velocities. Kim et al. (2012) [8] investigated the effects of flow inlet orientation using refrigerant R-134a in a parallel flow MCHX. Three inlet patterns were investigated as shown in fig.3.

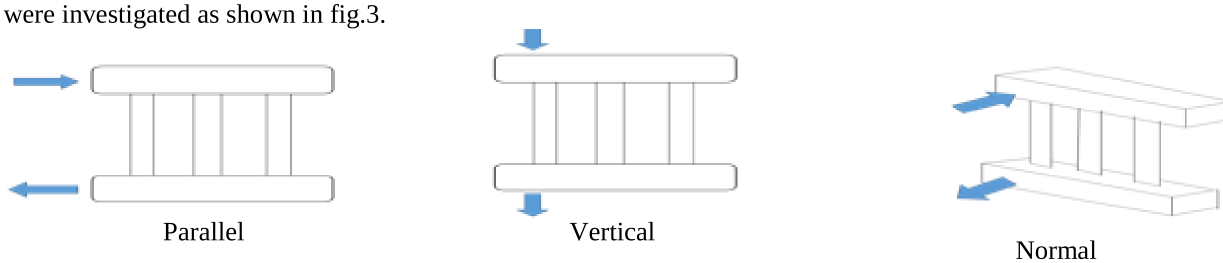


Fig 3. Flow Inlet Configurations

For parallel inlet configuration, liquid flow was concentrated on the frontal part of the header. For normal inlet configurations, more liquid was flown in the latter part of the header. In vertical configuration, liquid flow was more at the rear end of the header compared to normal inlet configuration. Kim et al. (2013) [9] also conducted a study to improve the flow distribution by using insert devices such as wire mesh, perforated plates and perforated tubes as in fig.4.

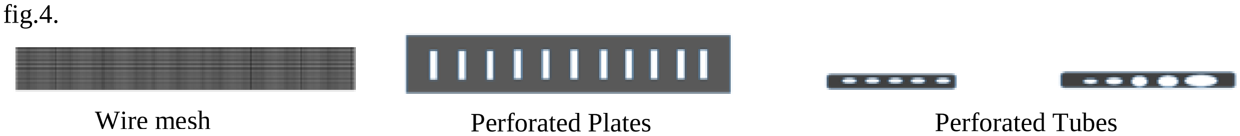


Fig.4. Various Types of Insert Devices

In case of downward flow, wire mesh and perforated plates didn't improve the flow distribution. The larger the perforation means less force to push water to the latter channels. So, tubes having less perforation was used as the insert device. It provided a good flow distribution. Nielsen et al. (2012)[12] investigated the effects of channel thickness. According to them, as the tube thickness was increased, severe hype in heat transfer coefficient was observed. This can be attributed to increase in fluid flow rates. The numerical model predicted an increase in performance when the spacing was reduced. The experimental study didn't prove this and the results dependency on thermal conductivity of aluminium is not explained properly. The results provided in this paper is only valid for aluminium and water based heat transfer fluid. Zou and Hrnjak (2013b) investigated experimentally the effects of upward flow in vertical header on the distribution of R134a into parallel microchannel tubes. Better distribution was observed when the tube was protruded half depth into the header. Hwang et al. (2007) [7] investigated the effects of geometry on refrigerant distribution in a horizontal header and vertically oriented microchannel heat exchanger. Three sets of branch tubes (18, 24 and 30) were studied. In general, better distribution was observed when number of tubes are more. Another study by them concluded that tube pitch is not significant in altering the two phase distribution in MCHX.

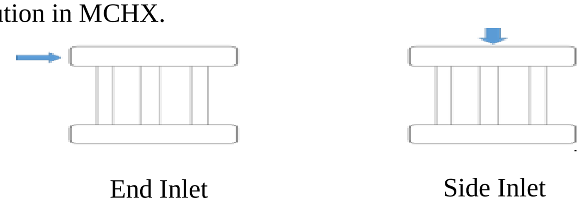


Fig 5. End Inlet and Side Inlet Configurations

Table 1: Previous studies on the distribution in header/tube configuration

Investigators	Header/Tube Configuration	D/D_h or A/A_h	Number of Tubes	Header/Tube Geometry	Refriegrants	Protrusion Depth	Comments
Kim and Sin (2006) [10]	Horizontal Round Header with Vertical Tubes	D/D_h= 12.9 A/A_h=1.9	30	Tube Pitch= 9.8mm Tube length=91 cm Header length= 400 mm	Air-Water	h/D= 0,0.25,0.5	Protrusion Depth and Header length discussed Flow investigated: Upward and Downward
Marchitto et al. (2007) [11]	Horizontal round Header and Vertical tubes	A/A_h= 1.17	16	N/A	Air-Water	h/D=0	Effects of Nozzles Flow Investigated- Upward
Ahmad et al.(2008) [1]	Horizontal Header and Vertical Tubes	N/A	8	Header length= 127 mm Tube Length= 1500mm	HFE 7100	h/D=0	Effects of operating conditions, header diameter and expansion devices Flow Investigated- Upward, Downward and Horizontal
Kim et al (2012) [8]	Horizontal Rounder header with vertical tubes	D/D_h= 12.9 A/A_h=1.9	10	Tube Pitch= 9.8mm Tube length=120 cm Header length= 150 mm	R134a	h/D=0.5	Effect of Inlet Configurations and Protrusion depths Flow Investigated- Downward
Kim et al. (2013) [9]	Horizontal Rounder header with vertical tubes	D/D_h= 12.9 A/A_h=1.9	10	Tube Pitch= 9.8mm Tube length=120 cm	R134a	h/D=0.5	Effect of Insert devices
Zou and Hrnjak (2013a) [14]	Vertical Header with Horizontal Tubes	D/D_h=30.8	5 inlet and 5 exit tubes	Tube Pitch= 13mm Tube length= 600mm Header length=170 mm	R-134a	h/D=0, 0.5, 0.75	Results for Vertical Header and Protrusion depth
Hwang et al (2007) [7]	Horizontal round Header with vertical tubes	D/D_h= 11.1	18,24,30	Tube pitch= 8/10/12 Tube length= 1000 mm	R-410A	h/D=0	Informations on tube numbers, tube pitch and inlet locations

*saturation temp (T_{sat}): Marchitto et al. (2008)[10] =60^0 C, Ahmad et al. (2009) [1] =57^0 C, Kim et al. (2012) [7] = 15^0 C, d= Zou and Hrnjak (2013a)[14] =10^0 C, Hwang et al. (2007) [6] =7.2^0 C

2.2 Operating Conditions

Marchitto et al. (2008) [11] investigated the effects of liquid and gas superficial velocities at the header inlet. The presence of inlet nozzle at the inlet of the distributor improved phase distribution into the parallel channels. The inlet nozzle produced a jet which eventually increased the two phase flow momentum at the header. Due to this arrangement, at low gas superficial velocity, the liquid flow distribution improved for the first pairs of channels. At higher superficial gas velocity, the two phase flow distribution became more uniform. However, for intermediate gas velocities, uneven flow distributions were observed. Kim et al. (2012) [8] studied the effects of operating conditions such as mass flux and vapor quality at different inlet configurations using R-134a as refrigerant. As mass flux was increased, the flow momentum is increased which forces the liquid to move to the rear part of the header which improved flow distribution. For vertical inlet configurations, the flow distribution is uniform at the lowest mass flux and mal-distribution is observed as it is increased. Strong swirl seems to be the reason for this trend. Due to the Swirl flow, denser liquid phase will be concentrated near the tube wall and lighter vapor phase near the tube center creating an annular flow. This result is not discussed properly in the paper and it will be highly desirable if they can validate the results. At low quality, vertical inlet yields uniform flow distribution for both liquid and gas. As the quality increases, the best configuration is normal inlet configuration. Parallel inlet configuration helps in distribution of the largest amount of liquid to the frontal part of the header. Zou et al. (2013)[17] explored the distribution of refrigerants R134a and R410A in microchannel heat exchangers with vertical header. At low mass flow rate, R410A distribution was better than the distribution of R134a and at high mass flow rate, vice versa. The paper also investigated the capacity degradation as a function of inlet mass flux and quality. Capacity degradation was increased as the mass flux was decreased and/or the quality was increased. Capacity degradation of R410a is better than that of R134a, but at higher mass flux, the trend was reversed. Brix et al. (2009) [3] investigated the effects of mal distribution of refrigerants in parallel evaporator channels on the heat exchanger performance by numerical simulations. They didn't consider two phase distribution in the header. As the two phase distribution in the header influences inlet quality distribution into the channels, the severity in the mal-distribution will be more than what they found with their numerical model. They used correlation which is only valid for qualities less than 0.7 to calculate the heat transfer coefficient on the refrigerant side in the two phase region. In actual case, at higher qualities, dry out may occur and heat transfer mechanisms will be different. Zou and Hrnjak (2014)[16] investigated the effects of different fluid properties on two phase flow distribution. As inlet mass flux increases and/or quality decreased, the distribution becomes better for all refrigerants with an exception for R410 at the highest quality too.

2.3 Flow patterns

A particular type of geometric distribution of the components is called a flow pattern or flow regime. Flow patterns are usually recognized by visual inspection. Flow patterns can be bubbly, slug, churn, annular and stratified as illustrated in the Fig.6. Flow patterns are important in determining whether the flow is evenly distributed or not.

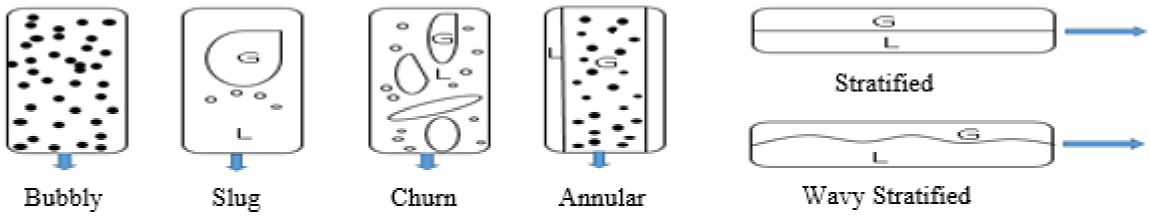


Fig.6. types of flow patterns

Ahmad et al. (2009) [1] did flow visualization experiment. For low mass flux and low quality, the flow was fully stratified. In such case, the flow was concentrated in the initial channels. When the liquid momentum was increased, a wavy stratified flow was observed at header inlet. In this type of flow pattern, due to increased momentum, the liquid moves till the end of the header filling the channel on its way having a weak jet effect. At higher liquid momentum, annular flow appears where the vapor was surrounded by thin film of liquid which provides for two phase maldistribution in MCHX. Kim and Sin (2006) [10] investigated effects of mass flux, vapor quality and protrusion depth on flow patterns in case of upward and downward flow (Fig.1.). The flow pattern at the header inlet was annular. Kim et al. (2012) [8] investigated the effect of inlet configurations (Fig.3) on flow distribution. For parallel and normal inlet configurations, stratified flow was observed whereas annular flow was observed for vertical inlet configuration. The annular flow was formed due to the impinging liquid jets. Zou et al (2014)[17] observed churn flow and annular flow of at the vertical header inlet using R-134a and R410A as refrigerant. He observed churn flow at low vapor qualities and annular flow at high qualities. The local churn flow throughout the header generated better distribution as liquid and gas phases showed better homogeneity. Even though churn flow was desirable, distribution of liquid and gas phases were not good at very low mass fluxes/quality. As the mass flux/quality was increased more and more, annular flow was identified which provided worst distribution. He used the term separated flow instead of annular flow. This is because of the reason that due to tube protrusion, annulus was not complete. Marchitto et al. (2008) [11] investigated the effect when inlet nozzle was inserted into the header. The flow pattern observed was slug flow. When the inlet restriction was more (when the nozzle diameter is less), annular flow regime formed inside the header. Dario et al. (2015) [6] investigated the effect of inlet feeding tube on flow patterns. For horizontal inlet feeding, bubbly and stratified flow patterns were observed at low mass flux and quality. Annular and churn flow patterns were observed at high mass flux and inlet quality. The appearance of churn flow at higher inlet and mass quality was discussed properly in the paper. For vertical inlet feeding, bubbly and slug flow patterns were identified. At higher values of operating conditions, similar results were obtained as compared to horizontal inlet feeding. At the highest value of mass flux and quality, mist flow was observed providing worst distribution. Chen et al (2012) [5] investigated two phase distribution in micro T channels. At low mass flux and inlet qualities, bubbly flow pattern was observed and as they were increased, churn flow was observed similar to many finding. As the flow pattern reaches annular, two phase inhomogeneity distribution reached highest.

2.4 Fluid Properties

Zou et al. (2013) [17] compared refrigerants R134a and R410 in the vertical header with h/D=0.5. At low mass flow rate, R410A provided better distribution whereas at high mass flow rate, R134a distribution was better. This can be attributed to R410A's higher liquid reach and even the tubes at the top were immersed in the liquid. At higher mass flow rates, due to higher momentum and liquid reach, R410A's liquid separation height was increased and many bottom tubes were depleted of liquid R410A. The results may not be accurate for horizontal headers and header having less protrusion depths. Zou and Hrnjak (2014)[16]investigated the effects of fluid properties on two phase flow and refrigerant distribution. They compared R245fa, R410A, R134a and R32. They found R245fa to be the best fluid which provided better two phase flow distribution. This can be attributed to fluid's low vapor density and high liquid density. This is just a speculation. The maldistribution caused by R245fa and R134a was only because of fluids inability to lift liquid to the top due to its high liquid density. This can be redeemed by increasing mass flux. R410A has better distribution compared to R32 because of its liquid reach.

3. ASSESSMENT OF TWO PHASE FLOW DISTRIBUTION MODELS:

Table 2: Equations for predicting liquid take-off ratios

Investigators	Correlation
Kim et al. (2012)	R134a: Parallel Inlet: $\frac{\dot{m}_{Tl_i}}{\dot{m}_{Hl_i}} = 2.78Re_g^{-0.719}(liquid); \frac{\dot{m}_{Tg_i}}{\dot{m}_{Hg_i}} = 3.66Re_g^{-0.955}(gas)$ Normal Inlet: $\frac{\dot{m}_{Tl_i}}{\dot{m}_{Hl_i}} = 2.01Re_g^{-0.550}(liquid); \frac{\dot{m}_{Tg_i}}{\dot{m}_{Hg_i}} = 3.38Re_g^{-0.920}(gas)$ Vertical Inlet: $\frac{\dot{m}_{Tl_i}}{\dot{m}_{Hl_i}} = 2.10Re_g^{-0.547}(liquid); \frac{\dot{m}_{Tg_i}}{\dot{m}_{Hg_i}} = 4.93Re_g^{-1.27}\ (gas)$
Zou and Hrnjak (2013a)	R134a: $\Gamma = 39389\ x_{in}^{1.122}\left(\frac{A_{min}}{A}\right)^{0.355} Re_{vM}^{-1.153}$
Byun and Kim (2011)	R410A: $\frac{\dot{m}_{Tl_i}}{\dot{m}_{Hl_i}} = 6.98Re_g^{-0.42}\ (liquid); \frac{\dot{m}_{Tg_i}}{\dot{m}_{Hg_i}} = 11.9Re_g^{-0.41}(gas)$
Zou and Hrnjak (2013b)	R410A: $\Gamma = 421989\ x_{in}^{1.248} Re_{vM}^{-1.447}$
Watanabe et al. (1995)	R11: $\frac{\dot{m}_{Tl_i}}{\dot{m}_{Hl_i}} = 2.74 * 10^{-5}\eta^2 - 0.0124\eta + 1.37$

Table 3: Conditions for which correlations were developed

Paper	Refrigerant	Mass Flux (kg/m^{2}s)	Quality	Tsat	Header/Tube geometry	Tube Protrusion, h/D
Kim et al. (2012) [8]	R134a	70-130	0.2-0.6	15 ^{0}C	Horizontal/Vertical	0.5
Zou and Hrnjak (2013a) [14]	R134a	92.26-276.79	0.2-0.8	10 ^{0}C	Vertical/horizontal	0.5 & 0.75
Zou and Hrnjak (2013b) [15]	R410A	21.80-127.3	0.2-0.95	5 ^{0}C	Vertical/horizontal	0.5
Byun and Kim (2011) [4]	R410A	50-70	0.3	10 ^{0}C	Vertical/horizontal	0
Watanabe et al. (1995) [13]	R11	60-100	0-0.4	N/A	Horizontal/Vertical	0

Table 4: Experimental studies against which the correlation predictions were validated/compared

Paper	Refrigerant	Mass Flux (kg/m^{2}s)	Quality	T_{sat}	Header/Tube geometry	Tube Protrusion, h/D
Kim et al. (2012) [8]	R134a	70-130	0.2-0.6	15 ^{0}C	Horizontal/Vertical	0.5
Zou and Hrnjak (2013a) [14]	R134a	92.26-276.79	0.2-0.8	10 ^{0}C	Vertical/horizontal	0.5 & 0.75
Zou and Hrnjak (2013b) [15]	R410A	21.80-127.3	0.2-0.95	5 ^{0}C	Vertical/horizontal	0.5
Byun and Kim (2011) [4]	R410A	50-70	0.3	10 ^{0}C	Vertical/horizontal	0
Watanabe et al. (1995) [13]	R11	60-100	0-0.4	N/A	Horizontal/Vertical	0
Ahmad (2009) [1]	HFE 7100	70-400	0.05-0.45	57 ^{0}c	Horizontal/Vertical	0
Kim and Sin (2006) [10]	Air-Water	70-200	02-0.6	N/A	Horizontal/Vertical	0,0.25,0.5
Kim et al. (2013) [9]	R134a	70-130	0.2-0.6	15 0C	Horizontal/Vertical	0.5

$$\Gamma_i = \frac{\dot{m}_{Tl_i}}{\dot{m}_{Hl_i}} ------------------ Eq. 1$$

3.1 Predictions of Liquid take-off Correlations

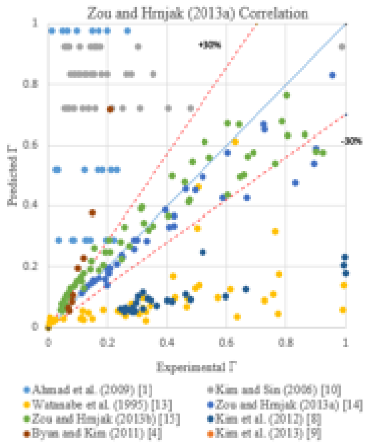


Fig 7: Scatter Plot for Zou and Hrnjak (2013a)

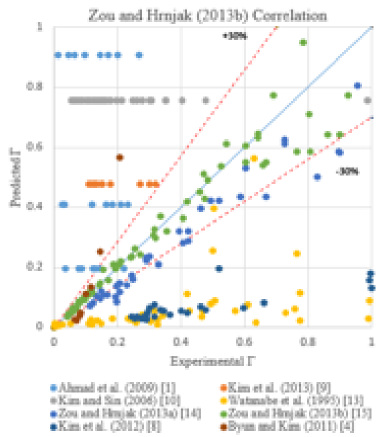


Fig 8: Scatter Plot for Zou and Hrnjak (2013b)

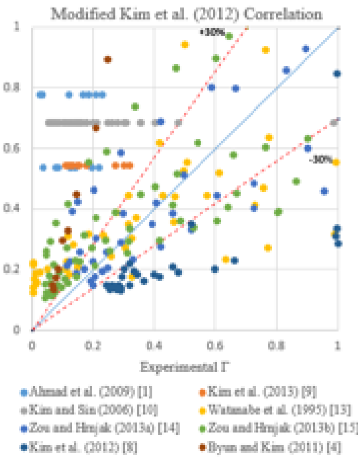


Fig 9: Scatter Plot for Kim et al. (2012)

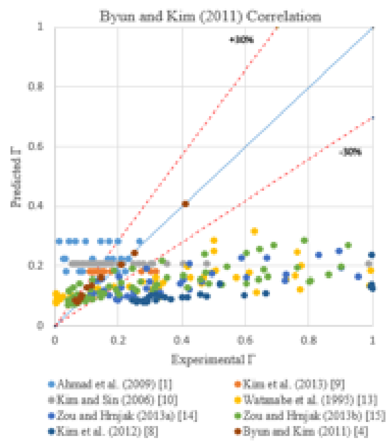


Fig 10: Scatter Plot for Byun and Kim et al. (2011)

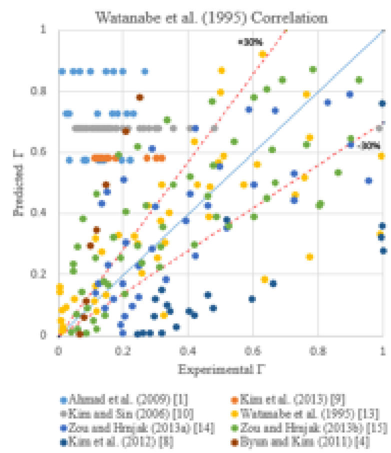


Fig 11: Scatter Plot for Watanabe et al. (1995)

The ratio of the liquid mass flow rate in a tube to that in the header immediately upstream of this tube is called liquid take-off ratio. Five correlations for predicting liquid take-off ratio (Γ) were developed by several researchers. Table 2 shows the equations for these correlations and Table 3 summarizes the operating and geometric conditions under which the correlations were developed. The correlation predictions were also compared to the results of several experimental studies, which are summarized in Table 4. Figs.7 through 11 represent the predictions of each of the five correlations against the data summarized in Table 4. Studying Tables 2, 3, 4, and Figs. 7-11, the following conclusions can be drawn:

Table 5: Summary of Correlation applicability to selected papers

Exp. study Model	Ahmad et al (2009) [1]	Kim and Sin (2006) [10]	Kim et al (2013) [9]	Watanabe et al. (1995) [13]	Byun and Kim (2011) [4]	Zou and Hrnjak (2013a) [14]	Zou and hrnjak (2013b) [15]	Kim et al. (2012) [8]
Modified Kim et al. (2012) [8]	×	×	×	✓	×	×	✓	×
Zou and Hrnjak (2013a) [14]	×	×	×	×	✓	✓	✓	×
Zou and Hrnjak (2013b) [15]	×	×	×	×	✓	✓	✓	×
Byun and Kim (2011) [4]	×	×	×	×	✓	×	×	×
Watanabe et al. (1995) [13]	×	×	×	✓	×	✓	✓	×

The Zou and Hrnjak (2013a)[14] and Zou and Hrnjak (2013b)[15] correlations for R134a and R410A provide excellent predictions for their own dataset (as seen in Figures 7 and 8). Only the correlations of Zou and Hrnjak (2013a and b)

[14, 15] capture the effect of vapor quality and tube protrusion depth in addition to the gas Reynolds number. This can explain, as discussed above, why they provide more accurate predictions compared to the other models. The Kim et al. (2012) [8] model provides three different expressions for the take-off ratio: for parallel inlet, normal inlet, and vertical inlet configurations (see Fig. 3). Since all the experimental works captured in Table 6 have parallel inlet arrangement, only their correlation for parallel inlet was considered in Fig. 9. Interestingly, the Kim et al. (2012)[8] correlation, as reported in their article, fails to predict their own experimental dataset satisfactorily. It is worth remarking that Fig. 8 is not based on the equations provided by Kim et al. (2012) [8], which appear in Table 4. If their equations are used as given, they result in extremely low predictions of the take-off ratio. Hence, the predictions were consistently multiplied by a factor of 100 in Fig. 8. This corrected model is referred to as 'Modified Kim et al. (2012)'. Even with this two orders of magnitude change, the modified Kim et al. (2012) correlation provides reasonable predictions only for the datasets of Zou and Hrnjak (2013b)[15]and Watanabe et al. (1995)[13]. Thus, it may be concluded that the applicability of the Kim et al. model to any data, including their own, is questionable. The Byun and Kim (2011) [3] correlation (Fig.10) correlation holds good only for their own dataset, but does very poorly for the other data. This can be partly explained by the fact that their model does not account for the effect of quality or tube protrusion depth. The Watanabe et al. (1995) [13] correlation (Fig.11) does well for their own data, and gives mixed results for the datasets of Zou and Hrnjak (2013b) [15] and Byun and Kim (2011)[3]. One reason for this is the mass flux range. It can also be explained by the different fluid properties of R11, R134a, and R410A. Liquid to vapor density of R-11 is much higher than that of R134a and R410A. Also Watanabe et al. (1995) [13] recommended that their model should not be used for Re < 1000 and Re>35000. None of the correlations predicted well for Ahmad et al. (2009) [1] and Kim and Sin (2006) [10], owing to the fact that they used air-water as refrigerants.

3.2 Applicability of Correlations to R134a and R410A

Each of the five correlations investigated was developed for a particular fluid. In the previous section, their applicability to different refrigerants and tube/header geometries were analyzed. In this section, the applicability of the correlations to specific refrigerants will be discussed.

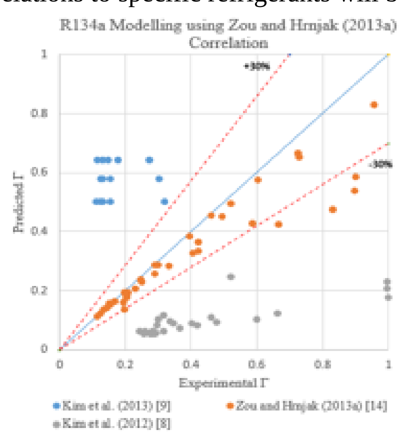


Fig. 12 Scatter Plot for Zou and Hrnjak (2013a) Corr. for R134a

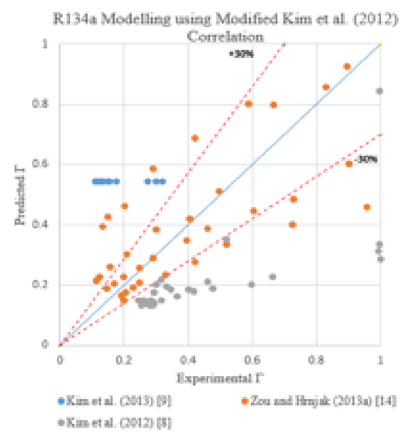
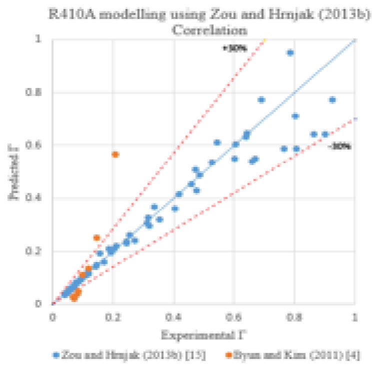


Fig.13. Scatter Plot for Kim et al. (2012) Corr. for R134a

Table 6: Applicability of Correlation to R134a

Applicability of Correlations to R134a								Recommendation
Exp. Study / Correlation	Kim et al (2013) [9]	Zou and Hrnjak (2013a) [14]	Kim et al. (2012) [8]	Exp. Study / Correlation	Kim et al (2013) [9]	Zou and Hrnjak (2013a) [14]	Kim et al. (2012) [8]	Zou and hrnjak (2013a) correlation can be recommended for vertical headers.
Zou and Hrnjak (2013a) [14]	×	✓	×	Modified Kim et al. (2012) [8]	×	✓	×	Kim et al. (2012) correlation's applicability is questionable for its own experimental dataset



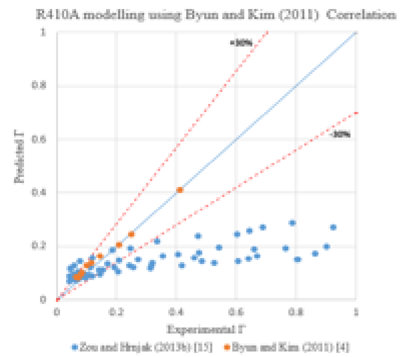


Fig. 14 Plot for Zou and Hrnjak (2013b) Corr. for R410A

Fig.15. Plot for Byun and Kim (2011) Corr. for R410A

Table 7: Applicability of Correlations to R410A

Applicability of Correlations to R410A						Recommendation
Exp. Study / Correlation	Byun and Kim (2011) [4]	Zou and hrnjak (2013b) [15]	Exp. Study / Correlation	Byun and Kim (2011) [4]	Zou and hrnjak (2013b) [15]	Zou and Hrnjak (2013b) is a very good correlation to predict liquid take off ratio of MCHX with vertical header geometry as can be seen in figs. 14 and 15. Inlet quality proves to be a prominent factor in flow distribution
Zou and Hrnjak (2013b) [15]	✓	✓	Byun and Kim (2011) [4]	✓	×	

4. CONCLUSION

A critical assessment of two-phase flow maldistribution in MCHX has been conducted. Factors affecting two phase-flow maldistribution were discussed. For downward flow through tubes, flow was evenly distributed when tubes were protruded up to the radius of the header. Tube protrusion helped liquid to flow to the rear end of the header thereby improving its distribution. Tube protrusion has negligible effect during upward flow. Improved flow distribution was observed when the fluid flow through tubes was vertically downward or horizontal compared to vertically upward flow. Insert devices that can be inserted into the header such as perforated plates and wire mesh do not improve flow distribution. However, perforated tubes can improve the flow distribution. Insert devices that can be mounted at inlet of the header or tubes such as inlet nozzle, orifice etc. helped in improving flow distribution. In general, flow was evenly distributed for high mass flux and low inlet quality with an exception in the case of refrigerant R410A which provided good flow distribution even at high quality. In the header, churn flow leads to improved flow distribution while annular flow leads to poorer flow distribution. More experimental investigations are required to understand the effect of fluid properties on two-phase flow distribution.

Table 8: Recommendations for future works on liquid take-off ratios

Correlations	x30% (Global)	Overall Comment	x30% (R134a)	Comment	x30% (R410A)	Comment
Modified Kim et al. (2012) [8]	20.2%	Applicability of Kim et al (2012) [8] is questionable as they didn't predict their own experimental dataset	25.6%	not recommended	*	
Zou and Hrnjak (2013a) [14]	29.4%	Recommended for vertical headers as it incorporated inlet quality and protrusion depth	39.0%	Recommended only for vertical headers	*	
Zou and Hrnjak (2013b) [15]	32.7%	Recommended as it incorporated inlet quality and protrusion depth	*		88.7%	Strongly recommended
Byun and Kim (2011) [4]	19.5%	not recommended	*		35.2%	not recommended
Watanabe et al. (1995) [13]	22.8%	Good for R-11 refrigerant	*		*	

NOMENCLATURE

A	cross-sectional area	(m^2)
D	header inner diameter	(m)
d	tube inner diameter	(m)
G	mass flux	(kg/m^2 s)
h	protrusion depth	(m)

Re	Reynolds number	
$\dot{m}$	Mass flow rate	(kg/s)
T	temperature	(^{0}C)
x	quality	
Γ	liquid take off ratio	
η	sqrt(Re_g)	

Subscripts

g	saturated vapor or gas
H	header
i	branch number
l	liquid
M	main pipe (header)
T	tube
v	vapor

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