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Flow Boiling Heat Transfer in Mini and Micro Channels - A State of the Art Review

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Abstract: A comprehensive review of flow boiling heat transfer characteristics of various working fluids in mini and micro channels is presented in this paper. Due to their high heat transfer and heat removal properties, two phase flows have been studied and applied into the electronics cooling systems. Correlations for two-phase heat transfer established by many researchers based on their experimental studies have been compared and indulged with conventional correlations in both the laminar and turbulent flow regimes. A plenty of working fluid, configurations of the channels and various range of parameters were included in this review. The survey involves over a distinct range of studies such as investigation of single phase, estimation of heat transfer in various sized channels, analytical studies in small tubes/channels, two-phase flow boiling in mini and micro channels, design and testing of micro channel heat sinks for electronic cooling. Further developments in existing research for future research based on this area of review have been established.

Keywords: Flow boiling, Two-phase flow, Heat transfer, Pressure drop, Refrigerants, Mini and Micro channels.

INTRODUCTION

Flow boiling heat transfer in mini and micro channels has got prominent importance in oflate years because of its potential for dissipating high heat fluxes especially in the micro electronics. Microsystems are significantly used in high heat flux situations due to their low cost and high potential applications in many fields such as space, communication, biology and industry. Micro channels are used in MEMS and high end micro processors cooling applications. The development of Micro-Electro-Mechanical devices(air bag acceleration sensors, HD readers), Micro-Opto-Electro-Mechanical devices(Micro endoscope) and Micro-Flow devices(micro heat exchanger, Micro heat pump systems, micro valves, micro cold plates, other micro components and sensors used in chemical analysis) have been encountered both in commercial and scientific applications during last fifteen years. The processes involving phase change like flow boiling heat transfer are predominant in such devices. The knowledge of thermal and flow behaviors on a micro scale with narrow passages have some remarkable role industrially. However the lacks of research work still in this area due to complexity of the phenomenon of flow boiling heat transfer. Object of most experimental work have been investigating a particular fluid and geometry of relevance to a specific heat exchanger. The cautious consideration of each parameter involving the moment in micro and mini channels must be studied systematically. The resulting errors may differ well due to entrance, exit effects, quality effects and difference in channel erosion in the various mini and micro channels with varying sizes, nature of flow and thermal boundary conditions, uncertainties in measuring instrumentation.

Flow boiling in normal sized channels:

The status of research for two-phase flow boiling in standard size tubes/channels has been established as it is a fundamental study of two-phase flow boiling in mini and micro channels. Chen[1] was developed the first common correlation for flow boiling heat transfer in originally sized channels which exposed about both nucleate boiling and two-phase forced convective boiling. A modified correlation over Chen[1] relation for flow boiling was established in tubes and annuli with 4300 data of refrigerants, water and ethylene glycol[2]. The flow boiling heat transfer characteristics on oil-free R22 was investigated in C-shape curved tube[3] and results of oil-free R22 show that the heat transfer coefficient in the tube are 10-20% lesser than those in straight smooth tube. The already existed heat transfer correlations were examined with experimental data of R-134a flow boiling in two small stainless steel tubes[4] and analyzed the three zone evaporation model up to quality 0.9. The model developed, did not predict satisfactorily the conditions of decreasing heat transfer coefficient at high quality and which are attributed to partial dryout.

The two phase flow boiling heat transfer characteristics of R410A-oil mixture and R22-oil mixture in the inside straight smooth tubes were reported[5,6]. The output reveal that the presence of lesser amount of oil may cause an enrichment in heat transfer coefficient at low vapor qualities, when a significant drop in boiling performance occurs at high vapor qualities for the high oil concentrations. The experimental data of the local heat transfer characteristics of R410A- oil mixture and R22-oil mixture flow boiling in the inside horizontal c-shape curved smooth tubes have been resulted[7.] In this study, the flow boiling heat transfer coefficient mode was developed in the inside c-shape tube depends on properties of refrigerant-oil and it agreed with 96% of the experimental data within the deviation of ±20%. Experiments of diabatic two-phase pressure drops and flow boiling for R22 and R410A were conducted in four horizontal flattened smooth copper tubes with varying heights[8]. They developed two- phase pressure drop model and compared with available correlations.

Flow boiling heat transfer in micro channels:

The term miniaturization has been played vital role in many commercial sectors as advanced technology such as micro heat pumps and pipes, biomedical engineering, aerospace and compact heat exchanger etc.

Tuckerman and Pease[9] introduced the micro channel heat sink technology first time by performing experiment on silicon based micro channel heat sink for electronic cooling. Then the experiment on flow steaming heat transfer was conducted in both mini and micro channels[10]. The effect of channel attrition is primitive in micro channel than mini channel. Common CHF correlation developed for mini, micro channels and showed that micro yielded higher CHF than mini with 0.3bar for micro channel and 0.03bar for mini channel. The flow boiling heat transfer for R-12 based on nucleation dominant mechanism has developed[11], which predicts the data with mean deviation 28.7% where the quality ranges from 0.6 to 0.8. A comparison was made between the circular and rectangular channels, it did not give much difference exists between the channels with same hydraulic diameter.

The flow boiling of methanol-water mixture was studied in rectangular stainless steel tubes[12]. It revealed that the flow velocity, concentration and channel dimensions enhance greatly the heat transfer coefficient at arrival of flow boiling and the partial nucleate boiling. The heat transfer correlations were developed for predicting boiling heat transfer in small diameter channels[13]. The flow steaming of R-134a has investigated in a bundle of 2mm diameter tubes[14]. The average heat transfer coefficient determined by data over the length of the tube in terms of mass flux, saturation temperature and heat flux. The flow steaming of methanol-water mixture through V-shaped micro channels was studied and experiment gave a best possible hydraulic diameter and groove angle[15]. It identified that the heat transfer and pressure drop were affected by flow velocity, groove angle and flow velocity. The flow boiling heat transfer coefficient of Freon R-11 and HCFC123 were examined in smooth copper tube with 1.95mmID[16]. This study results that heat transfer coefficient independent of mass flux and vapor quality. The paper was compared the available correlations and most of them identified that the nucleate boiling mechanism was dominant over wide range of flow condition due to low Reynolds number and liquid conductivity. The heat transfer correlation was proposed for flow boiling of R-113 in rectangular horizontal with low aspect ratios[17]. This paper showed the modified frictional pressure drop over L-M correlation and predicts data within the deviation of ±20%.

The two-phase flow of both air-water and steam-water systems were studied in circular micro channels[18]. The paper investigated experimentally the effect of surface contaminants and the wetability between the tube wall and the fluids. It also showed good agreement with the Armand correlation for air-water flow in larger tubes. The flow channels were classified first time into conventional channel, micro and mini channel by hydraulic diameter[19]. This also stated that flow boiling is established by both nucleate boiling and forced convective heat transfer mechanisms. The role of nucleate boiling in two-phase flow boiling heat transfer is concealed by two-phase flow. Experiment on boiling heat transfer was conducted for R-134a through small vertical tubes and found that nucleate boiling heat transfer coefficient was higher for 2.01mm than 4.26mm tube[20]. The saturated flow boiling heat transfer was examined in a water cooled three side heating micro channel heat sink with 21 parallel channels[21,22]. This study showed that the heat transfer coefficient decreased with increasing thermodynamic equilibrium quality and annular two-phase flow model. Chung and Kawaji[23] found that diameter between 100µm and 200µm seemed to be in the range corresponding to mini-to-micro scale transitions. This was confirmed by Saisorn and Wonguises[24]. The flow boiling heat transfer of CO_2 was measured in extruded micro channel tubes with 0.5m length and reported that increase in heat flux and temperature resulted in high heat transfer coefficient[25]. The model developed by combining the factors nucleate boiling, convective evaporation, post dryout heat transfer and predict data within the deviation of ±30%.

The existing correlations and experimental studies related to saturated flow boiling heat transfer in mini channels were reviewed[26]. Finally the review recommended the Chen[1] correlation, predicted data within ±25% error bar for four flow conditions. The model for predicting heat transfer coefficients was developed in mini and micro channels by combining both mechanisms[27]. The predicted data using model gave an average error 25.5%. Experiment on flow boiling was carried out in rectangular mini channel with hydraulic diameter of 0.89mm and investigated two-phase flow stability[28]. The refrigerant HFC-134a vapor-quality based flow boiling heat transfer coefficients was investigated in a micro channels cold plate evaporator since the working fluid has got wide microelectronics thermal management applications[29]. The heat transfer coefficient was found significantly with refrigerant quality and mass flow rate for the range of values investigated, but only slightly with saturation pressure 400-750 Kpa. The peak heat transfer coefficient observed for vapor quality 20%.

The flow boiling heat transfer characteristics of CO_2 and R-134a were investigated in rectangular multichannel with 1.08 to 1.54mm hydraulic diameter[30]. Results showed that average heat transfer coefficient of CO_2 increased around 53% when compared with that of R-134a and the heat transfer coefficient increased with decrease in hydraulic diameter. The three quality region flow boiling heat transfer correlation of R-134a was developed in the same rectangular heat sink channels which showed excellent predictions for water also[31]. The heat transfer characteristics of R-134a and R-407C were studied in horizontal mini channels with 0.83 and 2mm diameter[32]. The effects of heat flux, mass flux, vapor quality, saturation temperature and saturation pressure on heat transfer coefficient were determined. The flow boiling heat transfer of different refrigerants was examined[33] and showed that CO_2 affected heat transfer coefficient was higher than R-134a and R-22.

The heat transfer characteristics of CO_2 through 1.5mm and 3mm diameter of horizontal mini channels were reported[34]. In this study, nucleate boiling was predominant in low quality vapor region while convective boiling heat transfer appeared at high vapor quality region. Variation of heat transfer coefficient with respect to heat flux, mass flux, vapor quality, saturation temperature was discussed. The flow boiling heat transfer for R-134a was investigated in horizontal tubes with different diameters[35]. Study showed that nucleate boiling was dominant at low vapor quality region and convective boiling dominant at high vapor quality region. Flow boiling of water through 1.5mm diameter of vertical circular tube was studied experimentally and observed both nucleate and convective boiling mechanisms[36]. The indirect refrigeration cooling system was conducted to discuss flow boiling behavior using four different sized micro-channel heat sinks and wide range of operating conditions[37]. They revealed that small D_h increases total wetted area which decrease void fraction along the micro-channel. This study also showed that the cooling performance of the micro channel heat sink can be greatly enhanced by lowering the temperature of coolant entering the heat sink.

The flow boiling heat transfer coefficient of FC-72 was studied in micro channel heat sinks[38], which was designed for liquid cooling of electronic compounds and measured by varying the mass flux, heat flux, saturation temperature and vapor quality. Paper also discussed that many two phase pressure drop correlations used in research originated from Lockhart-Martinelli correlation[39], which has been modified by many investigation pursuits of better predictions for macro channels, but recent studies showed that this correlation produced poor prediction in small size channels. He introduced the effective viscosity with wall effects for modifying the existing correlations in micro channels based on data comparisons and yielded the greatest predictions with average mean deviation of 0.9% and 27%. This was compared with earlier models such as L-M correlation[39], Friedel model[40], Mishima and Hibiki correlation[41], Lee and Lee correlation[17] and showed the average mean deviation between -41% and 49.8%. This study was introduced new fluid surface parameter F_{f1}=0.747 for Fc-72 based on the present data to improve accuracy of the predictions with average mean deviations of 0.4% and 7%. The flow boiling experiments were conducted[42] and compared the results obtained from a 1.1mm diameter with 3-zone model[43] developed.

A model for heat transfer coefficient associated with flow boiling and hybrid boiling was developed[44]. Paper was compared experimental data of dielectric fluid PF5050 with proposed model and other existing correlations. The two phase flow boiling heat transfer for R-22, R-134a, R-410A, C_3H_8 and CO_2 in horizontal small tubes with quality up to 1 was investigated[45]. The paper was discussed about drawbacks on R-22 as an environmental conservation effort and studied some alternative refrigerants namely R-134a, R-410A, CO_2 and C_3H_8. Normally natural refrigerants can easily deplete layer since they do not have chlorine. The correlations developed earlier for evaporative refrigerants in mini channels such as Tran et al[11], Zhang et al[26], Peterson et al[25] and Yun et al[30] majorly contributed to nucleate boiling mechanism. The new model for forced convective boiling of refrigerants in small tubes based on super position model proposed and showed average mean deviation -0.48% after comparing with other existing correlations.

The heat transfer coefficient of R-134a refrigerant was studied during flow boiling in a horizontal circular mini-channel at high mass flow rates[46]. Also compared the prediction methods developed already. The flow boiling characteristics in a cross linked micro channel heat sink at low mass flux and high heat flux were investigated[47]. The two-phase pressure drop and flow boiling heat transfer coefficient of FC-72 increase with increasing exit quality at constant mass flux. Finally combined the two phase pressure drop and heat transfer data for comparing with previous existing correlation for straight micro channel heat sinks. The effect of heat flux, mass flux, vapor quality and saturation temperature on flow boiling heat transfer with refrigerants R-134a and R245fa in copper micro channels cold plate evaporators were studied[48]. The experimental data for refrigerant R-134a in channels with hydraulic diameter of 1.09mm already developed by Bertsch et al[29]. Bertsch et al[49] , Dupont et al[50], Kandlikar et al[51], Vlasie et al[52]. The published results show that the heat transfer coefficient increases with increasing heat flux, the effect of several other parameters such as vapor quality and mass flux have received less attention and shown opposition trends in the literature in some cases. This study compared experimental data against predictions from several existing correlations and showed reasonable agreement only with very few correlation.

The flow boiling heat transfer characteristics of R123 and R134a in a micro channels were investigated[53]. The range of vapor qualities (0.2 – 0.85) and different saturation pressures 158,208kpa for R123 and 900, 1100kpa for R134a were studied. The surface tension and liquid viscosity of R123 are nearly twice as large as those of R134a at ambient saturation temperature. Three recent heat transfer correlations[27,31,48] were compared with present experimental data. Ong and Thome[54] investigated three different refrigerants R-134a, R-236fa and R-245fa flowing through 1.03mm diameter. Results showed that heat transfer coefficient depends on heat flux at low vapor qualities and that on mass flux at high vapor qualities. R-134a gave high heat transfer coefficient followed by R-236fa and R-245fa was determined. The flow boiling heat transfer performance of CO_2 was focused in horizontal small bore tubes at high pressure since CO_2 has got much attention in heat pump, air conditioning and refrigeration[55]. Results showed that performance of CO_2 was as high as other refrigerants namely ammonia and isobutene.

The convective heat transfer coefficient in each flow boiling condition for FC-72 was determined in a single horizontal circular cross section micro channel[56]. Paper showed that heat transfer coefficient increased with increase of vapor quality at high vapor quality in the sub cooled boiling region and for the high and very high heat flux and low and medium mass flux. Satish G.Kandlikar[57] investigated the scale effects on flow boiling of water and FC-77 in micro channels with hydraulic diameter smaller than about 200μm. Paper studied the scale analysis to identify the relative effects of different (surface tension, evaporation momentum force) forces on the boiling process at micro scale. Further research on identifying the effects of turbulence transition in two phase flow is suggested. Enio P.Bandarra Filho[58] reviewed analyzed the physical properties, flow patterns, boiling heat transfer and two phase pressure drops of refrigerant/lubricant oil mixtures. The various parameters influenced by the Lubricant oil on convective boiling of refrigerants such as oil concentrations, mass velocity, vapor quality and geometric characteristics of the heat transfer tube were discussed.

Ayman Megahed[59] focused on the experimental investigation of flow boiling heat transfer characteristics for FC-72 in a silicon micro channel heat sink. Research determined the heat transfer coefficient for saturated flow boiling using thermo chromic liquid crystals measuring technique. Results showed that the heat transfer coefficient decreases sharply at low exit quality and then in remains almost constant as the exit quality increases. Flow boiling heat transfer and CHF data for R134a, R236fa and R245fa was investigated in single, horizontal channels of 1.03, 2.20 and 3.04mm diameter and compared it[60]. Early studies showed that macros channel flow boiling is an interaction of nucleate and convective boiling. The experimental study on flow boiling of water in 1.73mm ID of circular channel was conducted[61] and investigated the effect of pressure on flow boiling heat transfer by the range of 2-16 bar. They compared the high pressure experimental data with the existing correlations and proposed the annular flow model for predicting heat transfer coefficient which gave reasonably well agreement with experimental data.

Heat transfer and Pressure drop studies in small channels:

First part of Lee and Mudawar[62] investigated the pressure drop characteristics of R-134a in two phase heat sink as an evaporator in refrigeration cycle and showed practical advantages of micro channel heat sink for refrigeration. The frictional pressure drop correlation of refrigerant based nano fluid flow boiling inside horizontal smooth tube was developed[63]. R113 refrigerant and CuO nanoparticle were used for preparing refrigerant based nanofluid. Frictional pressure drop of refrigerant based nanofluid increases with increase of mass fraction of nanoparticle. The developed pressure drop correlation and predictions agree with 92% of the experimental data within the deviation of ± 15%.

The existing Pressure drop correlations were evaluated for working fluids in the wide range of hydraulic diameter[64]. Since the pressure drop in two phase channel flows find an important consideration in the design of heat exchangers, this study collected 2092 data from 18 papers and considered the working fluids include R123, R134a, R22, R236ea, R245fa, R404a, R407c, R410a, R507, CO2, water and air. The paper selected eleven two phase frictional pressure drop correlations for the range of Reynolds number of liquid from 10 to 37000 and Reynolds number of gas from 3 to 4 x 10^5 were taken. Results show that the accuracy of the L-M method[39], Mishima and Hibiki correlation[41], Zhange and Mishima correlation[65] and Lee and Mudawar correlation[31,62] in the laminar region is very close to each other. While the Muller-Steinhagen and Heck correlation[66] is the best among the evaluated correlations in the turbulent region. A modified Chisholm correlation[67] was also suited in the turbulent region with mean relative error about 29%. The new correlation and Muller-Steinhagen and Heck correlation[66] are very close to each other for refrigerants only. Friedel correlation[40] and the Zhang-webb correlation[68] are not very good for air and water; it gives good results for refrigerants.

The heat transfer in multiphase flow system owing to its widespread application in process industries were widely investigated[69-72]. The two phase pressure drop in the micro channel was studied and highly related to the flow pattern[73]. In this study, single rectangular micro channel was fabricated with different ratios of hydraulic diameters in order to look at the flow pattern. Experimental data used to assess seven different viscosity models. The pressure drop model was also developed for non-circular micro channels[74]. The semi-mechanistic pressure drop model for specific flow pattern was developed[75,76], which is based on three zone model[43]. A new correlation of two phase pressure drop was emphasized in silicon micro channel heat sinks for FC-72 refrigerant and predicted with mean absolute errors of 10.4% and 14.5% for laminar and turbulent flows[77]. The pressure drop across the heat sink was related to the exit quality for different mass fluxes and resulted that compared experimental data with predicted values of previously reported correlations in the literature to prove their validity.

The flow boiling heat transfer and pressure drop of pure HFC-152a were examined in a horizontal mini channel of 1mm diameter and proposed new Nusselt number correlation based on the Tran model[11] with average absolute deviation 3.7 and 11 percent[78]. In this study, the heat transfer coefficients of pure HFC-152a were determined as a function of vapor quality along the length of the micro channels. HFC-152a is classified as a mildly flammable refrigerant by ASHRAC34 and it has very good thermodynamic and transport properties that are close to R-134a. It was found that the correlation of Muller-Steinhagen and Heck correlation[66] gave a agreement for prediction of micro channels frictional pressure losses. Paper finally stated that developed model should be confirmed by conducting additional tests with different refrigerants and various channel diameters. The two-phase heat transfer coefficient of liquid-liquid systems have been investigated and established a new heat transfer correlation for two-phase systems, predict data within the minimum range of average absolute deviation[79,80].

The effects of mass flux, heat flux, saturation temperature and inner tube diameter on the pressure drop of the working refrigerants namely R-22, R-134a, R-410A, R-290 and R-744 were studied[81]. How the pressure drop was strongly affected by density, viscosity, surface tension and pressure of five working fluids in the horizontal circular small tubes were reported. New pressure drop correlation was developed on the basis of the L-M parameter method as a function of Weber number and Reynolds number by considering the laminar-turbulent flow conditions. Study finally showed that R-744 has lowest pressure drop among the present working refrigerants. Experimental data of pressure drop was compared with the earlier predictions from some existing correlations.

The overall studies on conventional and small channel flows in the past decade were categorized into various related areas and summarized in Table 1 below.

Table 1: Summary of existing work on two-phase flow boiling heat transfer and pressure drop in various channels given.

Model	Working fluid	Geometry and size of channel	Range of various parameter
Flow boiling in normal sized channels			
Gungor[2]	R-11, Water	Vertical and horizontal 3.0-32mm	12.4-61518 Kg/m^{2}s 0.35-91x10^3 Kw/m^2 0.08-202.6 bar
Shiferaw et al[4]	R-134a	Two ss tubes ID 4.26mm and 2.01mm	100-500 Kg/m^{2}s 13-150 Kw/m^2
Wei et al[6]	Refrigerant-oil mixture	Small tubes with ID of 6.34mm and 2.5mm	200-400 Kg/m^{2}s 3.2-14 Kw/m^2 Evaporation temp: 5^{0}C, Inlet quality: 0.1 to 0.8, Oil concentration: 0% to 5%
Haitao Hu et al[7]	Refrigerant – oil	horizontal C-shape curved smooth tube Curvature ratio: 50-70, OD:7mm, ID: 6mm, Length: 380mm, Radius:190mm	200-400 Kg/m^{2}s 6.93-15.12 Kw/m^2 Inlet quality: 0.1-0.7
Jesus Moreno Quiben et al[8]	R22 and R410A	Four horizontal flattened smooth copper tubes with two different heights of 2 and 3 mm. Equivalent diameters of flat tubes are 8.6, 7.17, 6.25 & 5.3mm	150 to 500 Kg/m^{2}s 6 to 40 Kw/m^2 5 ^{0}C
Flow boiling heat transfer in micro channels:			
Bowers et al[10]	R-113	Circular, diameter-2.45mm(mini), 510 µm(micro)	19-95ml/min 10-32 ^{0}C 0.03 and 0.3 bar
Tran et al[11]	R-12	Circular, 2.46mm	63-832 Kg/m^{2}s 3.6-59.5 Kw/m^2 1.2-6.6^{0}C and 5.1-8.3 bar

			63-832 Kg/m^{2}s 7.5-59.5 Kw/m^2 2.8-6.6 ^{0}C, Quality: 0-0.94
		Rectangular 1.7 x 4.06mm, d_h=2.4mm	44-505 Kg/m^{2}s 7.7-129 Kw/m^2 2.8-8.2 ^{0}C
	R-113	Circular, 2.92mm	50-400 Kg/m^{2}s 8.8-90.8 Kw/m^2 7.2-18.2 ^{0}C
Peng et al[12]	Water-methanol	Rectangular channel Width-0.1, 0.2, 0.3 and 0.4mm, Height-0.2 and 0.3, Length- 45mm, Hydraulic diameter-0.133-0.343mm	0.1 -4 m/s 18-27.5 ^{0}C
Kew and Cornwell[13]	R-141b	Circular 1.39-3.69mm	188-4800 Kg/m^{2}s 9.7-90 Kw/m^2 Quality: 0-0.95, 1000-7000 W/m^{2}K
Peng et al[15]	Water-methanol	V-shaped channel Hydraulic diameter- 0.2-0.6mm, Groove angle:30-60^0.	0.31-1.03 m/s for water and 0.12-2.14 m/s for methanol
Bao et al[16]	Freon R-11 and HCFC-123	Copper tube 1.95mmID	50-1800 Kg/m^{2}s 5-200 Kw/m^2 Vapor quality: 0-0.9, 200 to 500 Kpa, 3000 to 17000 W/m^{2}K
Lee and Lee[17]	R-113	Rectangular horizontal (0.4, 1, 2)mm x20mm	50-200 Kg/m^{2}s 0-15 Kw/m^2 Quality : 0.15-0.75
Serizawa et al[18]	Air-water, Steam-water	20,25 and 100 μm ID. 50 μm ID Circular tubes	0.003-17.52 m/s 0.0012-295.3 m/s superficial velocity
Huo et al[20]	R-134a	Circular Channel 2.01 and 4.26mm	100-200 Kg/m^{2}s 13-150 Kw/m^2 Quality: 0-0.9, 8000-42000 W/m^{2}K
Qu et al[21,22]	Deionized water	21 parallel channels 231x713 μm cross section	135-402 Kg/m^{2}s, 20-45 Kw/m^2 inlet temperature: 30-60^{0}C outlet pressure: 1.17 bar
Pettersen[25]	CO_2	25 circular flow channels of 0.8mmID and 0.5m length	190-570 Kg/m^{2}s 5-20 Kw/m^2 0-25 ^{0}C
Zhang et al[26]	R-11, R-12, R-113, water	Circular or Retangular channels range 0.78 - 6mm	23.4 – 2939 Kg/m^{2}s 2.95- 2511 Kw/m^2 0.101 – 1.21 MPa
Brutin and Tadrist[28]	n-pentane	Rectangular 0.5x4mm^{2}cross section, hydraulic diameter 0.89mm	125.6-15.7 Kw/m^2
Bertsch et al[29,49]	HFC-134a	17 parallel channels d_h=1.039mm	20.3 to 81 Kg/m^{2}s 0-20 W/cm2 8,9,18.7 & 29 ^{0}C
Yun et al[30]	CO_2	Rectangular channel D_h range from 1.08 to1.54mm	200 to 400 Kg/m^{2}s 10 to 20 Kw/m^2

			0,5 &10 ^{0}C
Lee and Mudawar[31,62]	R-134a	Rectangular channel 231x713 µm	127-654 Kg/m^{2}s 159-938 Kw/m^2 1.44-6.6 bar, 30-60 ^{0}C
Lie et al[32]	R-134a and R-407C	Horizontal tubes 0.83 and 2mm	200-1500 Kg/m^{2}s 5-15 Kw/m^2 5-15 ^{0}C
Choi et al[33,34]	R-134a, R-22, CO_2	Horizontal circular tube D_h range from 1.5 to3mm	200-600 Kg/m^{2}s 10-40 Kw/m^2 0-10 ^{0}C Quality 0-1
Lee and mudawar[37]	HFE 7100	Four different micr-channels 175.7 to 415.9 µm	670-6730 Kg/m^{2}s 2-20 g/s 0-750 Kw/m^2 -30-0 ^{0}C and 1.138 bar
Yonghee Jang et al[38]	FC-77	2mm 4mm, length=500mm	265.3-663.1 Kg/m^{2}s 132.7-439.6 Kg/m^{2}s 0.5-3W/cm^2 45-75 ^{0}C
Schwarzkopf et al[44]	Dielectric fluid PF5050	Inlet and exit hydraulic diameter of mesochannels 1.55 and 1.17 mm.	varied from 45 Kg/m^{2}s at the channel inlet to 110 Kg/m^{2}s at channel outlet 15-45 Kw/m^2 33.3-34.4^{0}C
Jong-Taek Oh et al[45]	R-22, R-134a, R-410A, C_3H_8 and CO_2.	Horizontal small tubes of 0.5, 1.5 and 3.0mm inner diameter	50-600 Kg/m^{2}s 5-40 Kw/m^2 0-15 ^{0}C
Sira Saisorn et al[46]	R-134a	Horizontal circular mini-channel 600mm long with diameter of 1.75mm stainless steel tube.	200-1000 Kg/m^{2}s 1-83 Kw/m^2 8,10 and 13 bar
Ayman Megahed[47]	FC-72	45 straight micro channels each with hydraulic diameter of 248 µm and heated length 16mm. Three cross links of width 500 µm	99 to 290 Kg/m^{2}s 7.2 to 104.2 Kw/m^2 Exit quality from 0.01 to 0.71
Bertsch et al[48]	R-134a and R245fa	1.09mm and 0.54mm.	20 to 350 Kg/m^{2}s 0 to 22 w/m2 8-30^{0}C
Sehwan et al[53]	R123 and R134a	Circular micro channel of 0.19mm ID.	314,392,470 Kg/m^{2}s 10,15,20 Kw/m^2
Mamoru Ozawa et al[55]	CO_2	Horizontal bore tubes 1mm,2mm and 3mm ID Length: 800, 1850 and 1700mm	200-700, 200-500 and 100-300 Kg/m^{2}s 10-50, 5-35 and 5-25 Kw/m^2 5.3-26.8^{0}C, 22-26.8 ^{0}C and 10-25.4 ^{0}C 4-6.7, 5-6.7 and 4.5-6.5 MPa
Gian Piero Celata et al[56]	FC-72	single horizontal circular cross section micro channel (480µm ID, 800µm OD, 102 mm long)	1500 Kg/m^{2}s 150 Kw/m^2

Satish G.Kandlikar[57]	Water and FC-77	D_h: 100-200µm	50-1000Kg/m^{2}s 1-10 Mw/m^2
Enio P.Bandarra Filho[58]	R-12, R-502, R-717, R-22, R-134a, R-407C, R-744, R-410A/ Lubricant oil	Review carried out from small channels(0.81,2,3mm) to 15.8mm	Range of parameter analyzed are: Oil concentration: 0-11% Mass flux: 10 to 1440 Kg/m^{2}s Heat flux: 1.5 to 60 Kw/m^2 Saturation temp: -40 to 27^{0}C
Ayman Megahed[59]	FC-72	45 rectangular micro channels were chemically etched with a depth of 276 µm, 225 µm width and 16mm length	341 to 531 Kg/m^{2}s 55.5 to 154.2 Kw/m^2
Ong et al[60]	R134a, R236fa and R245fa in	Single, horizontal channels of 1.03, 2.20 and 3.04mm diameter.	84-1600 Kg/m^{2}s 10-250 Kw/m^2 31^{0}C
Bang et al[61]	Water	Circular channel 1.73mm ID	100 Kg/m^{2}s , 50-160 Kw/m^2, 2-16 bar, 10000-35000 W/m^{2}K
Heat transfer and Pressure drop studies in small channels:			
Hao Peng et al[63]	R-113 and CuO nanoparticle	Horizontal smooth tube OD 9.52mm, Thickness 0.7mm, Length 1500mm	100-200 Kg/m^{2}s 3.08-6.16 Kw/m^2 Inlet vapor quality:0.2-0.7 Mass fraction of nanoparticle: 0%-0.5%
Licheng Sun et al[64]	R123, R134a, R22, R236ea, R245fa, R404a, R407c, R410a, R507, CO_2, water and air.	The hydraulic diameter ranges from 0.506 to 12 mm	Re of liquid from 10 to 37000 and Re of gas from 3 to 4 x 10^5
Chiwoong Choi et al[73]	Water-Nitrogen	hydraulic diameters of 141,143,304,322 and 490 µm.	liquid superficial velocities : 0.06-1m/s, gas superficial velocity 0.06-72m/s,-
Ayman Megahed et al[77]	FC-72	45 rectangular micro channels were chemically etched with a depth of 276 µm, 225 µm width and 16mm length	341 to 531 Kg/m^{2}s 60.4 to 130.6 Kw/m^2
Hamdar et al[78]	HFC-152a	mini channels of 1mm diameter	200 to 600 Kg/m^{2}s 10 to 60 Kw/m^2
Pamitran et al[81]	R-22, R-134a, R-410A, R-290 and R-744	horizontal small circular tubes of 0.5, 1.5 and 3mm ID, Length of tubes: 330 to 3000mm	50-600 Kg/m^{2}s 5-40 Kw/m^2 0-15 ^{0}C

Review mentioned that flow boiling of refrigerants/lubricating oil mixtures in mini and micro channels has been encountered in refrigeration, heat pump system and air conditioning. When compared to other working fluids oil greatly raises the two-phase pressure drops in micro channel-evaporators and this has significant effect on saturation temperature. But only few papers conducted experiments on flow boiling of refrigerants/lubricating oil mixtures in conventional channels and also minimum information about effect of oil is available in literature. So there is a need of more investigations on effect of oil mixtures to be carried out in mini and micro channels and also study of flow patterns of refrigerants/lubricating oil mixture should be conducted in future.

In order to improve the performance of refrigeration systems, refrigerant based nanofluids made by suspending nanoparticles have been used as a new kind of working fluid nowadays. The presence of nanoparticles may have effect on pressure drop characteristics of refrigerant flowing inside tubes, and then have impact on overall performance of heat exchangers of refrigeration systems. Study of flow boiling heat transfer of refrigerant based nanofluids in mini and microchannels should be explored in future since the pressure drop of such a fluid study governed only on normal sized channels.

CONCLUSION

A state of the art review on the flow boiling heat transfer and pressure drop studies of various kinds of refrigerants, water, air, oil and mixtures in differently sized tubes/channels is presented in this manuscript. Research on two-phase flow boiling of mixtures in mini and micro channels is comparatively lower than that of pure working fluids in same channels. According to this review, the following conclusions have been made as:

- Future study should be focused on modeling of flow boiling heat transfer and pressure drop of mixtures in mini and micro channels by incorporating the flow patterns, mechanisms of heat transfer, friction factor, dimensions of channels, quality of phases etc.
- Flow regime categorization of refrigerant flow in too many miniature channels need to addressed still.
- Phase change prediction technique on two-phase flow refrigerants while flowing in mini and micro channels for a wide range of thermal management applications need to be focused more.
- More fundamental studies about oil effect on flow boiling heat transfer, pressure drop and flow patterns of refrigerants/oil mixtures in mini and micro channels should be carried out in future.

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