# A New Two-Phase Multiplier for Flow Pressure Drop in Multiport Minichannel Condensers and Evaporators

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**ABSTRACT**

Due to flow maldistribution, the condensation and evaporation flow patterns in multiport minichannels are considerably different from single minichannels or macrochannels. This article compiled the friction pressure drop data from experimental phase-change investigations in multiport minichannel condensers and evaporators over the past two decades. The data was reduced to friction pressure gradients, and a new two-phase multiplier was proposed for estimating the phase-change pressure drop in multiport condensers and evaporators. Thirteen hundred and forty-four condensation pressure drop and six hundred and twenty-three evaporation pressure drop data from twenty-nine studies were correlated to yield four predictive two-phase multiplier equations in the laminar and turbulent flow regimes. The predictive correlations fit 67% of the laminar condensation and 80% of the turbulent pressure drop data within ±50%. Further, 57% of the laminar evaporation and 100% of the turbulent evaporation pressure drop data were fit within ±50%. The correlations were compared with widely published correlations and were a significant improvement. Meta-analysis revealed that multiport minichannels are most effective for reducing turbulent flow condensation pressure drop and laminar flow evaporation pressure drop. The compiled data and presented correlations and analysis should be helpful to the process, electronics packaging, aviation, and aerospace industries designing compact, lightweight, and high-efficiency condensers, and evaporators.

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## Introduction

Light-weight, compact, and highly efficient multiport minichannel condensers and evaporators rapidly replace conventional heat exchangers (HX) in the aviation, electronics, and aerospace industries. Minichannel-based multiport condensing heat exchangers and porous media-based thermosyphons are also increasingly deployed as condensing heat exchangers on spacecraft for humidity and temperature control. Due to their compactness and ultra-low weight, multiport minichannel-based condensers and evaporators also replace traditional air conditioners and refrigerators. The high aspect ratio (A/V) and higher heat transfer rates make them optimal for reducing compressor power consumption and global warming.

Due to flow maldistribution in the inlet and exit headers, the flow and pressure distribution in parallel minichannels, also known as multiport minichannels, can be substantially different from single or macro channels. This pressure variation is even more pronounced for phase-change HX such as condensers and evaporators. To minimize the pump or compressor pressure drop in such an HX, it is essential to identify the significant component of the pressure drop and reduce the same. Friction and acceleration pressure drops are the major components of the total pressure drop in multiport minichannel condensers and evaporators.

The dimensionless two-phase friction multiplier accurately expresses the phase-change friction pressure drop in condensers and evaporators. Lockhart and Martinelli [1] defined the two-phase multiplier $\phi_{LO}^2$ as the ratio of the two-phase pressure gradient to that with the liquid-only flow, as follows:

$$\phi_{LO}^2 = \frac{\left(\frac{dP}{dZ}\right)_{TP}}{\left(\frac{dP}{dZ}\right)_{LO}} \quad (1)$$

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## Nomenclature

| | |
|---|---|
| A | area ($m^2$) |
| ANOVA | analysis of variance |
| Bo | boiling parameter $\left(\frac{Gq''}{i_{fg}}\right)$ |
| C | Martinelli constant |
| cal | calculated value |
| CFD | computational fluid dynamics |
| CI | confidence interval |
| CMA | comprehensive meta-analysis |
| $C_L$ | liquid phase constant |
| $C_v$ | vapor phase constant |
| d | diameter (m) |
| exp | experimental value |
| f | friction factor |
| g | gravitational acceleration (9.81 $m/s^2$) |
| G | mass velocity $\left(\frac{\dot{m}}{A}\right)$ ($kg/m^2s$) |
| HX | heat exchanger |
| $i_{fg}$ | latent heat of vaporization (kJ/kg) |
| $I^2$ | heterogeneity index (I-squared) |
| La | Laplace parameter $\left[\frac{\left(\frac{\sigma}{g(\rho_L-\rho_v)}\right)^{0.5}}{d_h}\right]$ |
| $\dot{m}$ | mass flow rate (kg/s) |
| MBD | mean bias deviation $[\frac{1}{N}\sum\left(\frac{\exp-cal}{\exp}\right)]$ |
| n | exponent |
| N | count; sample size; the number of data |
| $N_{port}$ | number of parallel ports |
| P | pressure (Pa) |
| $P_{crit}$ | critical pressure (Pa) |
| $P_r$ | reduced pressure $\left(\frac{P}{P_{crit}}\right)$ |
| p-value | statistical heterogeneity parameter |
| q″ | heat flux ($W/m^2$) |
| $Re_L$ | liquid Reynolds number $\left(\frac{Gd_h}{\mu_L}\right)$ |
| $Re_{LO}$ | liquid-only Reynolds number $\left(\frac{G(1-x)d_h}{\mu_L}\right)$ |
| $Re_{TP}$ | two-phase Reynolds number $\left(Re_{TP}=\frac{Gd_h}{\mu_{TP}}\right)$ |
| $Re_v$ | vapor Reynolds number $\left(\frac{Gd_h}{\mu_v}\right)$ |
| RMSD | root mean square deviation $\left[\sqrt{\frac{1}{N}\sum\left\{\left(\frac{\exp-cal}{\exp}\right)^2\right\}}\right]$ |
| $Su_v$ | Suratman number $\left(\frac{\rho_v\sigma d_h}{\mu_v^2}\right)$ |
| T | temperature (K) |
| $Tau^2$ | absolute value of true variance (Heterogeneity) |
| $T_r$ | reduced temperature |
| V | volume ($m^3$) |
| We | Weber number $\left(\frac{G^2d_h}{\sigma\rho_L}\right)$ |
| $We_L$ | liquid-phase Weber number ($We_L=\frac{\mu_L G^2 d_h}{\sigma\rho_L}$) |
| $We_{TP}$ | two-phase Weber number $\left(We_{TP}=\frac{G^2d_h}{\sigma\rho_{TP}}\right)$ |
| x | vapor quality |
| Z | axial coordinate (m) |
| Z-value | statistical significance parameter |

***Greek symbols***

| | |
|---|---|
| $X_{lam,\ turb}$ | $\sqrt{Re_v^{-0.8}\left(\frac{C_L}{C_v}\right)\left(\frac{\dot{m}_L}{\dot{m}_v}\right)\left(\frac{\rho_L}{\rho_v}\right)\left(\frac{\mu_L}{\mu_v}\right)}$ ($C_L = 16$ and $C_v = 0.046$ for $Re_{LO} < 1000$ and $Re_v > 2000$; $C_L = 0.046$ and $C_v = 0.046$ for $Re_{LO} > 2000$ and $Re_v > 2000$; $\dot{m}_L = G(1-x)A$ and $\dot{m}_v = GxA$) |
| $X_{turb,\ turb}$ | $\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_v}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_v}\right)^{0.1}$ $\mu$ = dynamic viscosity (Pa.s) |
| $\mu_{TP}$ | two-phase viscosity $\left[\mu_{TP}=\left(\frac{x}{\mu_v}+\frac{1-x}{\mu_L}\right)^{-1}\right]$ |
| $\phi$ | two-phase pressure drop multiplier |
| $\rho$ | density ($kg/m^3$) |
| $\rho_{TP}$ | two-phase density ($\rho_{TP}=\frac{x}{\rho_v}+\frac{1-x}{\rho_L}$) |
| $\sigma$ | surface tension (N/m) |

***Subscripts***

| | |
|---|---|
| h | hydraulic |
| L | liquid |
| lam, turb | Laminar liquid, and turbulent vapor flow |
| LO | liquid-only |
| sat | saturated state |
| TP | two-phase |
| turb, turb | turbulent liquid, and turbulent vapor flow |
| v | vapor |

$$\left(\frac{dP}{dZ}\right)_{LO}=\frac{2f_{LO}G^2}{d_h\rho_{LO}} \tag{2}$$

The Moody [2] and Filonenko [3] equations for friction factors in smooth pipes for laminar and turbulent flows are:

$$f_{LO}=\frac{16}{Re_{LO}}(Re_{LO}\le 2300) \tag{3}$$

$$f_{LO}=\left(1.82\log_{10}Re_{LO}-1.64\right)^{-2}(Re_{LO}>2300) \tag{4}$$

The two-phase multiplier $\phi_{LO}^2$ in Eq. (1), deduced from the two-phase friction pressure drop gradient $(dP/dZ)_{TP}$ can be used to compare the flow pressure drop in an enhanced HX relative to an equivalent smooth round tube of the same hydraulic diameter $d_h$. Well-designed thermohydraulic designs yield low values of $\phi_{LO}^2$ for phase-change pressure drop and yield higher overall thermal efficiencies.

Since most of the existing correlations are based on limited data, this article compiled the experimental adiabatic friction pressure drop data during condensation and evaporation from experimental investigations in the past two decades. The two-phase friction pressure drop gradient $(dP/dZ)_{TP}$ was reduced to the liquid-only Reynolds number, $Re_{LO}$, based two-phase friction multiplier $\phi_{LO}^2$ and predictive correlations for the same were proposed. The new correlations based on a comprehensive database were compared with widely published correlations and significantly improved the existing knowledge. Meta-analysis was also performed on the compiled data to determine the statistical accuracy and relevance of multiport mini-channels for condensation and evaporation heat

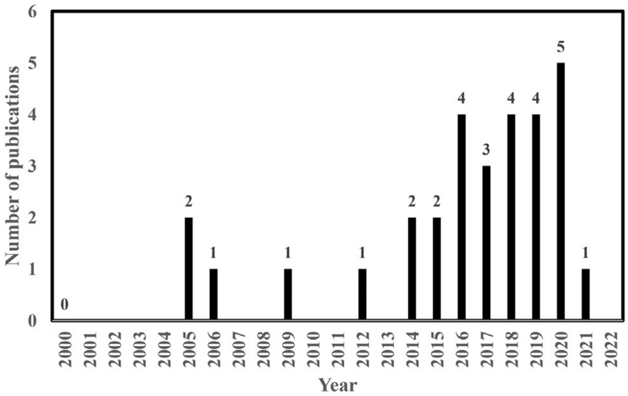


**Figure 1.** Publication record by year.

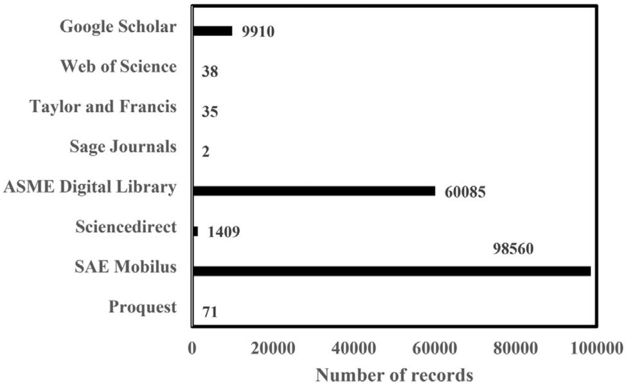


**Figure 2.** Database search by source and number of records.

transfer. Subsequent sections of the article will discuss the sources of the compiled data, state-of-the-art in the last two decades, regression and meta-analysis, and validation of the correlations.

## Sources and filtering

Nine comprehensive databases, including Proquest, SAE Mobilus, ScienceDirect, ASME Digital Library, SAGE Journals, Taylor and Francis, Google Scholar, Springer, and Web of Science, were searched to collect experimental works on multiport minichannel condensers and evaporators. A basic keyword search yielded 84,729 records which were further filtered by focusing only on phase-change studies in multiport assemblies to twenty-nine articles. Only experimental studies from the last two decades that reported two-phase pressure drop variation with vapor quality were chosen, while earlier seminal works were used for comparison and evaluation. Local and surface-averaged measurements were collected for regression analysis, correlation development, and statistical meta-analysis. Figures 1 and 2 depict the publication record by year and source.

## Multiport minichannel condensers

Numerous experimental condensation pressure drop investigations in multiport minichannel condensers were reported by researchers [4–21] in the past two decades. Most of those investigations were for laminar condensation [4–21], while a few reported turbulent condensation [4–13, 15–19, 21] friction pressure drop measurements.

Cavallini et al. [4] reported friction pressure drop gradients for condensation of R236ea, R134a, and R410A in a 1.4 mm diameter multiport minichannel condenser. Experimental friction pressure drop measurements were conducted at a saturation temperature $T_{sat} = 40\,°C$, mass flux $G = 200–1400\,kg/m^2s$, and vapor quality $x = 0–1$. The experimental friction pressure drop data and the deduced two-phase multiplier compared well with published correlations for all refrigerants except R410A. No new correlation was reported.

Park and Hrnjak [5] reported an adiabatic pressure drop during condensation of $CO_2$ in 0.89 mm diameter multiport minichannel condensers. Friction pressure gradient was measured at a saturation temperature of $T_{sat} = -15\,°C$, mass flux $G = 200–600\,kg/m^2s$, and vapor quality $x = 0–0.9$. The measured friction pressure drop increased with the mass velocity G and vapor quality x, decreasing with the saturation temperature $T_{sat}$. No new correlations were proposed.

Sakamatapan and Wongwises [6] measured condensation pressure drops of R134a in a 1.1 mm and 1.2 mm diameter multiport minichannel condenser. The pressure gradient was measured at a mass flux $G = 340–500\,kg/m^2s$, saturation temperature $T_{sat} = 40\,°C$, and vapor quality $x = 0.1–0.9$. It was reported that the local heat flux strongly affected the friction pressure gradient. A new two-phase friction factor correlation was proposed and successfully validated against widely reported correlations based on limited data.

Belchi et al. [7] investigated the friction pressure drop during condensation of R32 and R410A in a 1.16 mm diameter horizontal multiport minichannel condenser. The experiments were conducted at a mass flux $G = 470–800\,kg/m^2s$ and vapor quality $x = 0.1–0.9$. Widely reported correlations validated the limited data. No new correlations were proposed for the two-phase multiplier.

Belchi et al. [8] conducted condensation pressure drop experiments in a 1.16 mm diameter multiport minichannel condenser with R32 and R410A. The friction pressure drop was measured at a mass flux $G = 350–800\,kg/m^2s$, saturation temperature $T_{sat} =$

30–40 °C, and vapor quality $x = 0.1–0.9$ and was compared with existing correlations. No new correlations for the two-phase friction multiplier were proposed.

Jige et al. [9] reported condensation pressure drop with R134a, R32, R1234Ze(E), and R410A in a 0.85 mm diameter multiport minichannel condenser. The experiments were conducted at mass flux $G = 100–500$ kg/m$^2$s, saturation temperature $T_{sat} = 60$ °C and vapor quality $x = 0.1–0.9$. The condensation friction pressure gradient was reduced to a new friction factor correlation. The correlation based on limited data was compared successfully with existing correlations.

Belchi et al. [10] studied the condensation of propane in a 1.16 mm diameter multiport minichannel condenser. The condensation friction pressure gradient was measured at $G = 175–350$ kg/m$^2$s, heat flux q” = 15.76–32.25 kW/m$^{2,}$ and $T_{sat} = 30$ °C, 40 °C, and 50 °C. The data was reduced to new correlations. The limited data-based correlations were compared with widely reported correlations. No correlations were developed for the two-phase multiplier.

Bohdal et al. [11] conducted condensation pressure drop experiments in two 0.64 mm diameter multiport minichannel condensers with 4 and 8 parallel channels. The R407C condensation friction pressure gradient data in the range of $G = 126–1117$ kg/m$^2$s and at $T_{sat} = 35$ °C were not validated against widely reported correlations. No new correlations were developed for the two-phase multiplier.

Belchi and Gomez [12] investigated the condensation of R410A and R32 in a ten port, 1.16 mm diameter multiport minichannel condenser. The friction pressure gradient measured at $T_{sat} = 45$ °C and in the range $G = 350–710$ kg/m$^2$s was not correlated and compared with widely reported correlations. No new correlations were presented for the two-phase multiplier.

Rossato et al. [13] reported the condensation pressure drop gradient in 36 minichannels of 1.6 mm hydraulic diameter inside a bar and plate heat exchanger. The R1234ze(E) and R32 condensation pressure drop at $T_{sat} = 40$ °C and in the range $G = 55–275$ kg/m$^2$s was compared with existing correlations. No new correlations were reported for the two-phase multiplier.

Rahman [14] measured the condensation pressure drop in multiport minichannels and microfin tubes. The R134a condensation pressure gradient in a 0.81 mm diameter, 20 channel, multiport minichannel was correlated and compared with existing correlations. The experiments were conducted at a mass flux of $G = 50–200$ kg/m$^2$s, vapor quality $x = 0.1–0.8$, and saturation temperature $T_{sat} = 35$ °C. A new two-phase multiplier correlation was proposed based on the limited data in multiport minichannels with and without fins.

Kim [15] proposed a new correlation for the normalized pressure gradient in terms of the hydraulic diameter $d_h$, mass velocity G, number of ports

$N_{port}$, and the vapor quality x. The condensation pressure gradient for R410A in three flat multiport aluminum minichannel condensers with hydraulic diameters varying from 0.78 to 0.95 mm, was successfully compared with existing models. The condensation friction pressure gradient was measured at a mass flux $G = 100–400$ kg/m$^2$s, vapor quality $x = 0.2–0.8$, and saturation temperature $T_{sat} = 45$ °C.

Knipper et al. [16] reported condensation pressure drop gradients in two multiport minichannels with 0.77 mm and 0.91 mm hydraulic diameters. The R134a condensation pressure drop data were compared with widely reported correlations. The condensation friction pressure drop increased in multiport minichannel condensers with fins, while the overall thermal efficiency was lower due to lower heat transfer rates. No new correlation was proposed for the two-phase multiplier. The experiments were conducted at a mass flux $G = 200–800$ kg/m$^2$s, saturation temperature $T_{sat} = 40$ °C, and vapor quality $x = 0.1–0.9$.

Belchi [17] conducted condensation experiments with R134a, R513A, and R1234yf in a 1.16 mm multiport minichannel condenser. The condensation friction pressure gradient was measured at three different saturation temperatures of $T_{sat} = 40$ °C, 50 °C, and 60 °C, and mass velocities $G = 470–710$ kg/m$^2$s. The data were evaluated with existing two-phase models. The measured condensation pressure gradient was higher for R134a, while the corresponding heat transfer rate was lower due to the higher latent heat.

Jige et al. [18] investigated the condensation pressure drop of a binary mixture of R32 and R1123 in 0.82 mm and 1.16 mm diameter multiport minichannel condensers in the mass velocity range of $G = 50–400$ kg/m$^2$s and a saturation temperature $T_{sat} = 40$ °C. The measured friction pressure drop gradient was compared with existing correlations, and no new correlation was reported for the two-phase multiplier.

Kruzel et al. [19] reported pressure drop measurements in a 0.64 mm diameter multiport minichannel condenser. The R404A condensation friction pressure gradient was measured in the mass velocity range $G = 758–1335$ kg/m$^2$s and at a saturation temperature $T_{sat} = 42.5$ °C. No new correlations were reported.

Nalbandian et al. [20] experimentally studied the impact of the channel size and shape on the

**Table 1.** Multiport minichannel condenser pressure drop data.

| Study | Fluid | No. of data Laminar | Turbulent | % of data | Experimental uncertainty |
|---|---|---|---|---|---|
| Cavallini et al. [4] | R134a, R236ea, and R410A | 29 | 23 | 3.87% | 18% |
| Park and Hrnjak [5] | $CO_2$ | 39 | 11 | 3.72% | 9.7% |
| Sakamatapan and Wongwises [6] | R134a | 45 | 14 | 4.39% | ±6.4% |
| Belchi et al. [7] | R32 and R410A | 26 | 12 | 2.83% | 11.9% |
| Belchi et al. [8] | R32 and R410A | 36 | 98 | 9.97% | 11.9% |
| Jige et al. [9] | R134a, R1234Ze(E), R32, and R410A | 179 | 35 | 15.92% | Not available |
| Belchi et al. [10] | R290 | 68 | 31 | 7.37% | 11.9% |
| Bohdal et al. [11] | R407C, R134a, and R404A | 53 | 1 | 4.01% | Not available |
| Belchi and Gomez [12] | R32 and R410A | 32 | 56 | 6.55% | 11.9% |
| Rossato et al. [13] | R1234Ze(E) | 49 | 1 | 3.72% | ±1.3% |
| Rahman [14] | R134a | 63 | 0 | 4.69% | Not available |
| Kim [15] | R410A | 25 | 3 | 2.08% | ±4.3% |
| Knipper et al. [16] | R134a | 34 | 8 | 3.13% | ±6% |
| Belchi [17] | R134a, R1234yf, and R513A | 58 | 56 | 8.48% | 11.9% |
| Jige et al. [18] | R32, and the mixture of R32 and R1123 | 102 | 25 | 9.45% | Not available |
| Kruzel et al. [19] | R404A | 11 | 13 | 1.79% | Not available |
| Nalbandian et al. [20] | R134a and R1234yf | 70 | 0 | 5.21% | Not available |
| Kim et al. [21] | R404A, R448A, R449A, R454C, and R455A | 28 | 10 | 2.83% | ±0.4% |

condensation heat transfer and pressure drop in multiport minichannel condensers. Surface tension didn't impact the condensation pressure drop significantly. The experiments were conducted at a saturation temperature $T_{sat} = 30\,°C$, mass flux $G = 100–600\,kg/m^2s$, and vapor quality $x = 0.2–0.9$.

Kim et al. [21] reported a condensation pressure drop in a 0.8 mm diameter multiport minichannel condenser in the mass velocity range of $G = 380–760\,kg/m^2s$ and at a saturation temperature $T_{sat} = 45\,°C$. Several refrigerants with low global warming potential, such as R-448A, R-449A, R-455A, and R-454C, were condensed in the condenser with average vapor quality x varying between 0.2 and 0.8. No new correlations were proposed for the two-phase multiplier.

Table 1 summarizes all the compiled condensation data in the laminar and turbulent flow regimes [4–21].

Very few correlations [6, 9, 14] have been proposed in the past two decades. Since all these equations were based on minimal data, new and improved correlations based on a comprehensive and exhaustive database are necessary. The following sections propose improved correlations for predicting the two-phase multiplier, which can be used to estimate the condensation friction pressure drop in multiport minichannel condensers. Meta-analysis of the compiled data to detect inherent heterogeneity and publication bias and determine the effectiveness of multiport minichannel condensers will be discussed.

## Laminar condensation pressure drop: Regression analysis and correlation development

The laminar flow ($Re_{LO} < 2300$) pressure drop data compiled from eighteen sources [4–21] were analyzed to develop predictive correlations for estimating the two-phase multiplier $\phi^2_{LO}$ and correlating it with several fundamental and derived parameters such as the hydraulic diameter $d_h$, mass velocity G, number of parallel ports $N_{port}$, vapor quality x, and the Martinelli parameter for turbulent liquid and turbulent vapor flow $X_{turb,\ turb}$. The liquid-only Reynolds number $Re_{LO}$ for most data was in the range of 1000 to 2300. Hence, the turbulent Martinelli parameter valid for $Re_{LO} > 1000$ was chosen to yield a better fit to the data. Several regression models such as power law, non-linear, log-linear, non-parametric, analysis of variance (ANOVA), and others were deployed to model the compiled data. Equation (5), a significant modification of the Kim [15] model, best fit the collected data.

$$\phi^2_{LO} = 0.009 X^{0.92}_{turb,\,turb} d_h^{2.3} x^{1.23} G^{0.83} N^{1.3}_{port} \tag{5}$$

As shown in Figure 3, Eq. (5) fit the data at a mean bias deviation (MBD) of 18.8% and a root mean square deviation (RSMD) of 46.6%. It fit 11.6% of the data within ±10%, 38.6% of the data within ±30%, and 67.3% of the data within ±50%. Equation (5) is valid for the liquid-only Reynolds number $Re_{LO} = 22–2299$, mass velocity $G = 50–1335\,kg/m^2s$, vapor quality $x = 0.02–0.97$, hydraulic diameter $d_h = 0.5–1.6\,mm$ and number of parallel channels $N_{port} = 4–37$. It includes the Martinelli parameter $X_{turb,\ turb}$ and significantly improved the Kim [15] model and overall fit. In contrast, the Kim [15] equation fit only 6.5% of the data within ±30% and 10.4% within ±50%. Although the MBD at 39.6% was comparable to Eq. (5), the corresponding RSMD was much worse at 140.5%, resulting in a poor fit to the compiled data.

The compiled data were also compared with widely reported correlations, shown in Figure 4a–f. As shown

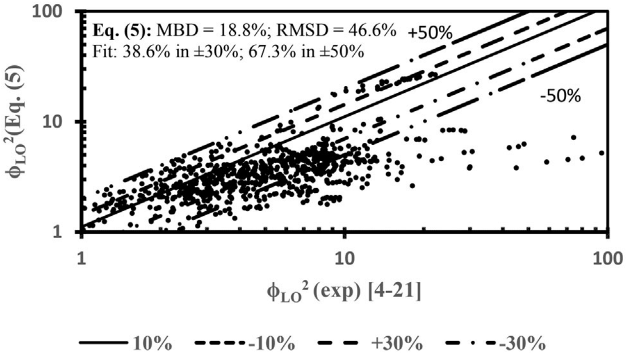


**Figure 3.** Predictive correlation (Eq. (5)) for two-phase multiplier for laminar condensation in multiport minichannels.

in Figure 4a, the Lockhart and Martinelli [1] correlation poorly fits the compiled data. At an MBD of $-2746.3\%$ and RMSD of 9418.4%, their correlation fit only 2.9% of the gathered data within ±30%, while 3.9% of the data was included within ±50%. Although the Lockhart and Martinelli [1] correlation is based on two-phase and two-component flows, no phase change processes were investigated. The absence of phase-change data and the constant regression parameter C in the Lockhart and Martinelli correlation may have resulted in severe underprediction.

A comparison with the Mishima and Hibiki [22] correlation is shown in Figure 4b. Their correlation was also a poor fit for the compiled data. At an MBD of $-1711.4\%$ and RSMD of 6397.9%, the Mishima and Hibiki [22] correlation fit 8% of the collected data within ±30% and 12.6% within ±50%. Although their correlation modified the Lockhart and Martinelli [1] correlation constant C, it's based on data from air-water flow in vertical multiport minichannels. The poor fit to the data from condensing flows could be due to the lack of friction pressure drop due to condensation or phase change. This lack of phase-change data may have resulted in the significant overprediction of the compiled data.

Evaluation of the compiled data with the Zhang [23] correlation is shown in Figure 4c. Similar to the Mishima and Hibiki [22] correlation, Zhang [23] modified the constant C in the Lockhart and Martinelli correlation [1] with the Laplace parameter La. The boiling pressure drop data-based predictive correlation was a poor fit to the compiled condensation data at an MBD of $-4077.5\%$ and RMSD of 12,954%. The Zhang [23] correlation fits 1% of the gathered data within ±50%.

The Lee and Mudawar [24] correlation was based on flow boiling pressure drop during evaporation of R134a in a microchannel evaporator and was also a poor fit to the compiled condensation pressure drop data. Their correlation modified the constant C in the Lockhart and Martinelli [1] equation with the liquid Weber number $We_L$. As shown in Figure 4d, the correlation for laminar liquid and turbulent vapor condensing flows in minichannels fit 17% of the compiled condensation pressure drop data within ±30% and 22% within ±50% at an MBD of $-1403.1\%$ and RSMD of 6797.5%. Weber number is significant for modeling pool boiling and is generally a poor parameter for modeling condensing flows. The liquid Weber number $We_L$ could have resulted in the poor fit of their correlation to the compiled condensation pressure drop data.

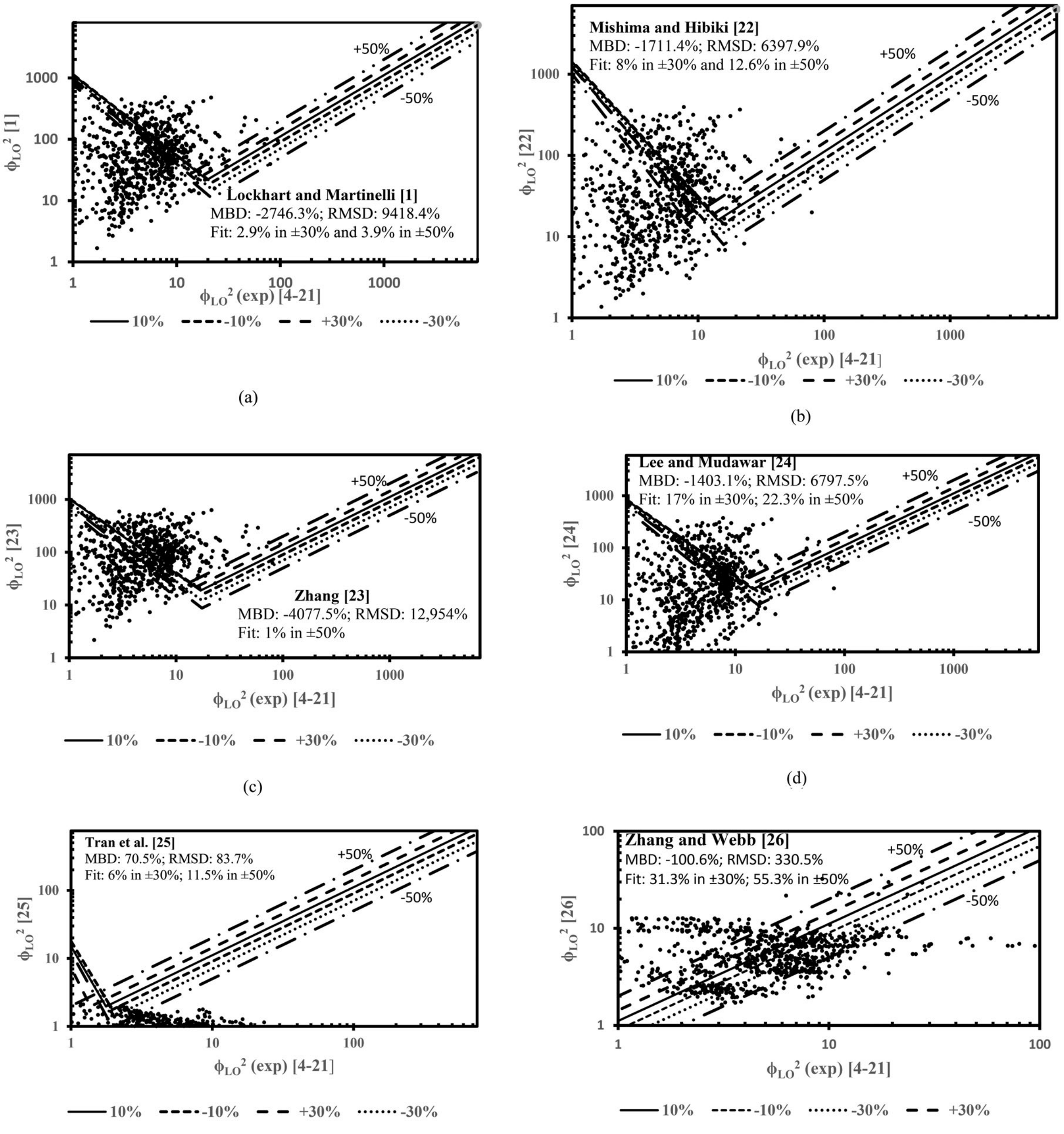
The condensation friction pressure drop data were evaluated with the Tran et al. [25] correlation and shown in Figure 4e. Their correlation is based on the condensation friction pressure drop of R12, R113, and R134a and is valid for the liquid-only Reynolds number $Re_{LO} = 500–2500$. It fit 6% of the data within ±30% and 11.5% within ±50%. At an MBD of 70.5% and RSMD of 83.7%, the Tran et al. [25] correlation yielded the lowest mean deviation of all the equations compared with the current data. The hydraulic diameter of the multiport minichannels tested by Tran et al. [25] varied from $d_h = 2.4–2.9\,\text{mm}$ and was higher than the diameter of the channels in the compiled studies. The higher diameter may have yielded different condensation flow patterns and droplet sizes than the collected studies, indicating the data's deviation.

As shown in Figure 4f, the Zhang and Webb [26] correlation fit 31.3% of the compiled data within ±30% and 55.3% within ±50%. It was the best possible fit of all the widely reported correlations at an MBD of $-100.6\%$ and RSMD of 330.5%. The reduced pressure-based correlation for the two-phase multiplier probably incorporated the effects of the fluid saturation temperature, pressure, and vapor quality more accurately than the other widely reported correlations and yielded a fit comparable to Eq. (5).

All the correlations discussed in this section and their validity are given in Table 2 [1, 15, 22–26].

## Meta-analysis of laminar condensation pressure drop in multiport minichannel condensers

Meta-analysis was performed on all the compiled studies for condensation pressure drop [4–21] in the laminar flow regime in multiport minichannels. The comprehensive meta-analysis (CMA) software developed by Biostat, Inc., was used to perform the analysis. It is a statistical tool that analyzes a given data



(a) (b) (c) (d) (e) (f)

**Figure 4.** Comparison with widely reported correlations for laminar condensation pressure drop in multiport minichannels: (a) Lockhart and Martinelli [1]; (b) Mishima and Hibiki [22]; (c) Zhang [23]; (d) Lee and Mudawar [24]; (e) Tran et al. [25]; (f) Zhang and Webb [26].

set's heterogeneity and reliability and highlights any hidden publication bias.

Given the weightage (15.92%), the Jige et al. [9] study was chosen as the control group, while the remaining studies [4–8, 10–21] were selected as the study group. Since many variables are affecting the pressure drop during condensation in multiport minichannel condensers, a composite parameter, $X_{turb,\ turb}^{-1.22} d_h^{1.36} x^{-1.1} G^{-0.171} N^{0.99}$ was chosen as the control variable. To include all the investigations, a meta-analysis was performed on the compiled studies [4–21] at an average liquid-only Reynolds number $\mathrm{Re}_{LO} = 957$ and a corresponding control variable of 0.0055. The forest plot and the cumulative forest plot of the analysis are shown in Figures 5 and 6, respectively.

The random model-based meta-analysis in Figure 5 indicates that the multiport minichannel condenser intervention technique is statistically insignificant. The analysis result is shown by the cumulative diamond at the bottom of the figure. Straddling the lower and upper limits of −2.046 and 0.338, the 95% confidence interval (CI) band crosses the null line (0). This indicates that the true effect size of the analysis lies in the computed 95% CI band, and no statistical significance can be attributed to the analysis. The compiled studies

**Table 2.** Predictive correlations for laminar flow condensation pressure drop in multiport minichannels.

| Study | Deviation | | |
|---|---|---|---|
| | MBD | RMSD | Fit |
| Current study (Eq. (5))<br>$\phi_{LO}^2 = 0.009\mathrm{X}_{turb,\ \ turb}^{0.92} d_h^{2.3} \mathrm{x}^{1.23} G^{0.83} N_{port}^{1.3}$<br>($d_h$ in mm)<br>($\mathrm{Re}_{LO} = 22$–$2299$, $G = 50$–$1335$ kg/m$^2$s, $x = 0.02$–$0.97$, $d_h = 0.5$–$1.6$ mm, and $N_{port} = 4$–$37$) | 18.8% | 46.6% | 11.6% in ±10%; 38.6% in ±30%; 67.3% in ±50%. |
| Kim [15]<br>$\frac{\left(\frac{dP}{dZ}\right)_{TP}}{\left(\frac{dP}{dZ}\right)_{TP,0.95}} = 0.4 d_h^{-3.75} G^{-0.06} x^{0.01} N^{0.22}$<br>$(dP/dZ)_{TP,\ 0.95}$: Condensation friction pressure gradient in a 0.95 mm multiport minichannel<br>($\mathrm{Re}_L = 2400$–$5200$, $G = 100$–$400$ kg/m$^2$s, $N_{port} = 9$–$18$, $x = 0.2$–$0.85$, $d_h = 0.78$–$0.95$ mm) | 39.6% | 140.5% | 6.5% in ±30%; 10.4% in ±50% |
| Lockhart and Martinelli [1]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>$C = 12$ for $\mathrm{Re}_{LO} < 2000$ and $\mathrm{Re}_v > 2000$<br>($G = 50$–$1500$ kg/m$^2$s, $T_{sat} = 21$–$29\,^\circ$C, $\mathrm{Re}_{LO} = 1.5$–$124{,}000$ and $\mathrm{Re}_v = 7$–$86{,}500$) | −2746.% | 9418.4% | 2.9% in ±30%; 3.9% in ±50% |
| Mishima and Hibiki [22]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>$C = 21(1\text{-}e^{-0.319d})$ (d in mm)<br>($G = 50$–$1500$ kg/m$^2$s, $x = 0$–$1$, $\mathrm{Re}_{LO} = 90$–$12{,}204$ and $\mathrm{Re}_v = 5$–$12{,}200$) | −1711.4% | 6397.9% | 8% in ±30%; 12.6% in ±50% |
| Zhang [23]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>$C = 21(1\text{-}e^{-358/La})$<br>($G = 50$–$1500$ kg/m$^2$s, $x = 0$–$1$, $\mathrm{Re}_{LO} = 90$–$12{,}204$ and $\mathrm{Re}_v = 5$–$12{,}200$) | −4077.5% | 12,954% | 1% in ±50% |
| Lee and Mudawar [24]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>$C = 1.45 Re_L^{0.25} We_L^{0.23}$<br>$We_L = \frac{\mu_L G^2 d_h}{\sigma \rho_L}$<br>($G = 127$–$654$ kg/m$^2$s, $q'' = 31.6$–$93.8$ kW/m$^2$, $\mathrm{Re}_L < 2300$ and $\mathrm{Re}_v > 2300$) | −1403.1% | 6797.5% | 17% in ±30%; 22.3% in ±50% |
| Tran et al. [25]<br>$\phi_{LO}^2 = 1 + \left(4.3\mathrm{X}_{lam,\ \ turb}^2 - 1\right)\left[La(1-x)^{0.875} + x^{1.75}\right]$ ($d_h$ in mm)<br>($G = 33$–$832$ kg/m$^2$s, $q'' = 2.2$–$129$ kW/m$^2$, $\mathrm{Re}_{LO} = 500$–$2500$ and $x = 0.2$–$0.9$) | 70.5% | 83.7% | 6% in ±30%; 11.5% in ±50% |
| Zhang and Webb [26]<br>$\phi_{LO}^2 = (1-x)^2 + \frac{2.87x^2}{P_r} + 1.68x^{0.25}(1-x)^2 P_r^{-1.64}$<br>($G = 200$–$1000$ kg/m$^2$s, $T_{sat} = 20$–$65\,^\circ$C, $\mathrm{Re}_{LO} < 2300$, $P_r = 0.25$–$0.51$, and $x = 0.17$–$0.93$) | −100.6% | 330.5% | 31.3% in ±30%; 55.3% in ±50% |

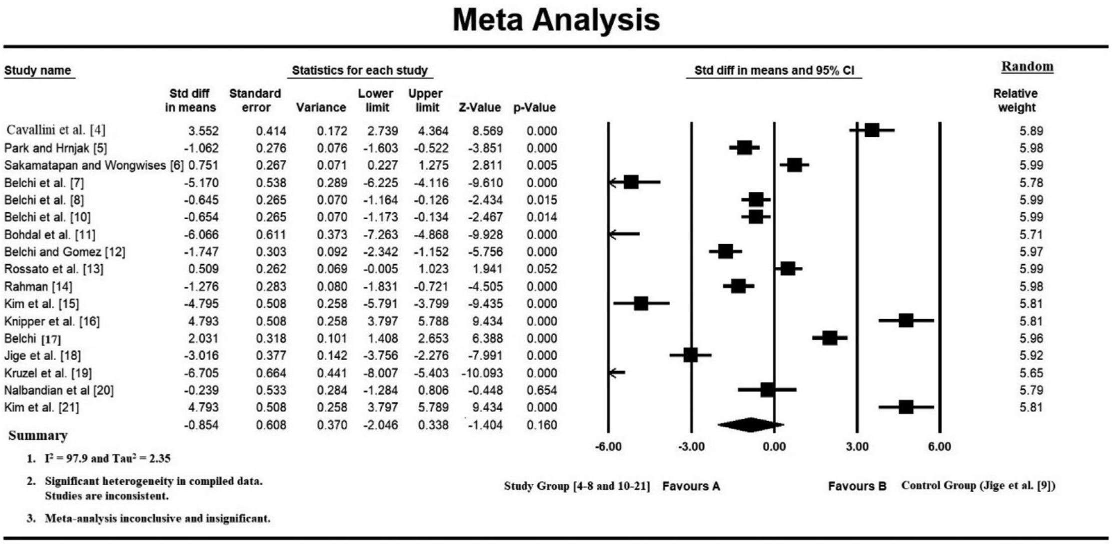
[4–21] demonstrated no statistical relevance for using multiport minichannel condensers for lowering the condensation friction pressure drop for laminar flows. As shown in Figure 6, the cumulative meta-analysis also supports the same conclusion.

## *Turbulent condensation pressure drop: Regression analysis and correlation development*

Friction pressure drop data for turbulent flow condensation in multiport minichannel condensers were compiled from sixteen studies [4–13, 15–19, 21] and analyzed with various linear and non-linear regression models. The Kim [15] equation was modified with the Martinelli parameter for turbulent flow $\mathrm{X}_{\mathrm{turb,\ turb}}$ to predict the two-phase multiplier for turbulent condensation friction pressure drop in multiport minichannel condensers.

$$\phi_{LO}^2 = 507.76\mathrm{X}_{turb,\ \ turb}^{-1.22} d_h^{1.36} x^{-1.1} G^{-0.171} N_{port}^{0.99} \tag{6}$$

As shown in Figure 7, Eq. (6), which is valid for the liquid-only Reynolds number $\mathrm{Re}_{LO} = 2301$–$15{,}138$, fit 29.1% of the data within ±10%, 68.4%

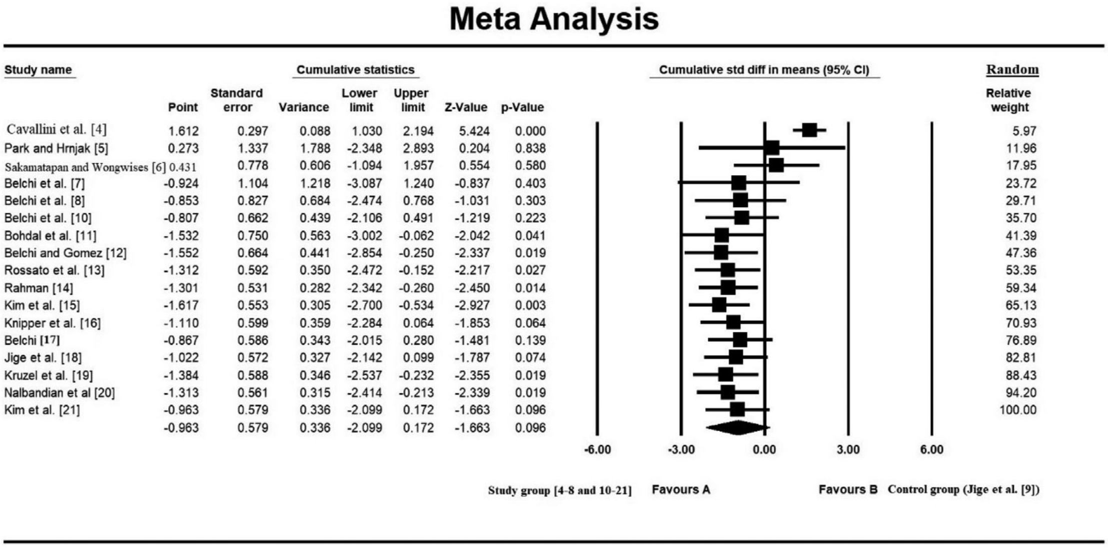


| Study name | Std diff in means | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Random Relative weight |
|---|---|---|---|---|---|---|---|---|
| Cavallini et al. [4] | 3.552 | 0.414 | 0.172 | 2.739 | 4.364 | 8.569 | 0.000 | 5.89 |
| Park and Hrnjak [5] | -1.062 | 0.276 | 0.076 | -1.603 | -0.522 | -3.851 | 0.000 | 5.98 |
| Sakamatapan and Wongwises [6] | 0.751 | 0.267 | 0.071 | 0.227 | 1.275 | 2.811 | 0.005 | 5.99 |
| Belchi et al. [7] | -5.170 | 0.538 | 0.289 | -6.225 | -4.116 | -9.610 | 0.000 | 5.78 |
| Belchi et al. [8] | -0.645 | 0.265 | 0.070 | -1.164 | -0.126 | -2.434 | 0.015 | 5.99 |
| Belchi et al. [10] | -0.654 | 0.265 | 0.070 | -1.173 | -0.134 | -2.467 | 0.014 | 5.99 |
| Bohdal et al. [11] | -6.066 | 0.611 | 0.373 | -7.263 | -4.868 | -9.928 | 0.000 | 5.71 |
| Belchi and Gomez [12] | -1.747 | 0.303 | 0.092 | -2.342 | -1.152 | -5.756 | 0.000 | 5.97 |
| Rossato et al. [13] | 0.509 | 0.262 | 0.069 | -0.005 | 1.023 | 1.941 | 0.052 | 5.99 |
| Rahman [14] | -1.276 | 0.283 | 0.080 | -1.831 | -0.721 | -4.505 | 0.000 | 5.98 |
| Kim et al. [15] | -4.795 | 0.508 | 0.258 | -5.791 | -3.799 | -9.435 | 0.000 | 5.81 |
| Knipper et al. [16] | 4.793 | 0.508 | 0.258 | 3.797 | 5.788 | 9.434 | 0.000 | 5.81 |
| Belchi [17] | 2.031 | 0.318 | 0.101 | 1.408 | 2.653 | 6.388 | 0.000 | 5.96 |
| Jige et al. [18] | -3.016 | 0.377 | 0.142 | -3.756 | -2.276 | -7.991 | 0.000 | 5.92 |
| Kruzel et al. [19] | -6.705 | 0.664 | 0.441 | -8.007 | -5.403 | -10.093 | 0.000 | 5.65 |
| Nalbandian et al [20] | -0.239 | 0.533 | 0.284 | -1.284 | 0.806 | -0.448 | 0.654 | 5.79 |
| Kim et al. [21] | 4.793 | 0.508 | 0.258 | 3.797 | 5.789 | 9.434 | 0.000 | 5.81 |
|  | -0.854 | 0.608 | 0.370 | -2.046 | 0.338 | -1.404 | 0.160 |  |

**Summary**

1. $I^2 = 97.9$ and $Tau^2 = 2.35$
2. Significant heterogeneity in compiled data.
   Studies are inconsistent.
3. Meta-analysis inconclusive and insignificant.

**Figure 5.** Meta-analysis of laminar condensation pressure drop [4–21] in multiport minichannels at $Re_{LO} = 957$.



| Study name | Point | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Random Relative weight |
|---|---|---|---|---|---|---|---|---|
| Cavallini et al. [4] | 1.612 | 0.297 | 0.088 | 1.030 | 2.194 | 5.424 | 0.000 | 5.97 |
| Park and Hrnjak [5] | 0.273 | 1.337 | 1.788 | -2.348 | 2.893 | 0.204 | 0.838 | 11.96 |
| Sakamatapan and Wongwises [6] | 0.431 | 0.778 | 0.606 | -1.094 | 1.957 | 0.554 | 0.580 | 17.95 |
| Belchi et al. [7] | -0.924 | 1.104 | 1.218 | -3.087 | 1.240 | -0.837 | 0.403 | 23.72 |
| Belchi et al. [8] | -0.853 | 0.827 | 0.684 | -2.474 | 0.768 | -1.031 | 0.303 | 29.71 |
| Belchi et al. [10] | -0.807 | 0.662 | 0.439 | -2.106 | 0.491 | -1.219 | 0.223 | 35.70 |
| Bohdal et al. [11] | -1.532 | 0.750 | 0.563 | -3.002 | -0.062 | -2.042 | 0.041 | 41.39 |
| Belchi and Gomez [12] | -1.552 | 0.664 | 0.441 | -2.854 | -0.250 | -2.337 | 0.019 | 47.36 |
| Rossato et al. [13] | -1.312 | 0.592 | 0.350 | -2.472 | -0.152 | -2.217 | 0.027 | 53.35 |
| Rahman [14] | -1.301 | 0.531 | 0.282 | -2.342 | -0.260 | -2.450 | 0.014 | 59.34 |
| Kim et al. [15] | -1.617 | 0.553 | 0.305 | -2.700 | -0.534 | -2.927 | 0.003 | 65.13 |
| Knipper et al. [16] | -1.110 | 0.599 | 0.359 | -2.284 | 0.064 | -1.853 | 0.064 | 70.93 |
| Belchi [17] | -0.867 | 0.586 | 0.343 | -2.015 | 0.280 | -1.481 | 0.139 | 76.89 |
| Jige et al. [18] | -1.022 | 0.572 | 0.327 | -2.142 | 0.099 | -1.787 | 0.074 | 82.81 |
| Kruzel et al. [19] | -1.384 | 0.588 | 0.346 | -2.537 | -0.232 | -2.355 | 0.019 | 88.43 |
| Nalbandian et al [20] | -1.313 | 0.561 | 0.315 | -2.414 | -0.213 | -2.339 | 0.019 | 94.20 |
| Kim et al. [21] | -0.963 | 0.579 | 0.336 | -2.099 | 0.172 | -1.663 | 0.096 | 100.00 |
|  | -0.963 | 0.579 | 0.336 | -2.099 | 0.172 | -1.663 | 0.096 |  |

**Figure 6.** Cumulative meta-analysis of laminar condensation pressure drop [4–21] in multiport minichannels at $Re_{LO} = 957$.

in ±30%, and 80.5% of the data within ±50% at an MBD of −7.1% and RSMD of 42.8%. In contrast, as shown in Figure 8a, the Kim [15] equation fits only 11% of the compiled data within ±50% and at an MBD of 4.6% and RSMD of 302%. Similar to Eq. (5), adding the Martinelli parameter modeled the two-phase flow regime better and improved the overall fit. Equation (6) is valid for the liquid-only Reynolds number $Re_{LO}$ = 2301–15,138, hydraulic diameter $d_h$ = 0.64–1.6 mm, vapor quality x = 0.009–0.857, mass velocity G = 175–1400 kg/m$^2$s, and number of parallel ports $N_{port}$ = 4–37.

The compiled turbulent flow condensation friction pressure drop data were compared with widely reported correlations. Figure 8b shows the comparison

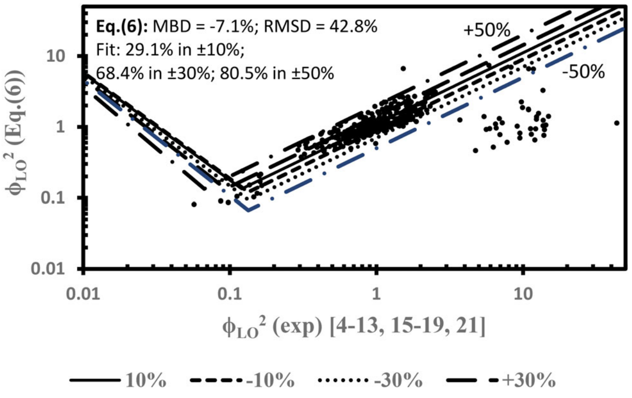
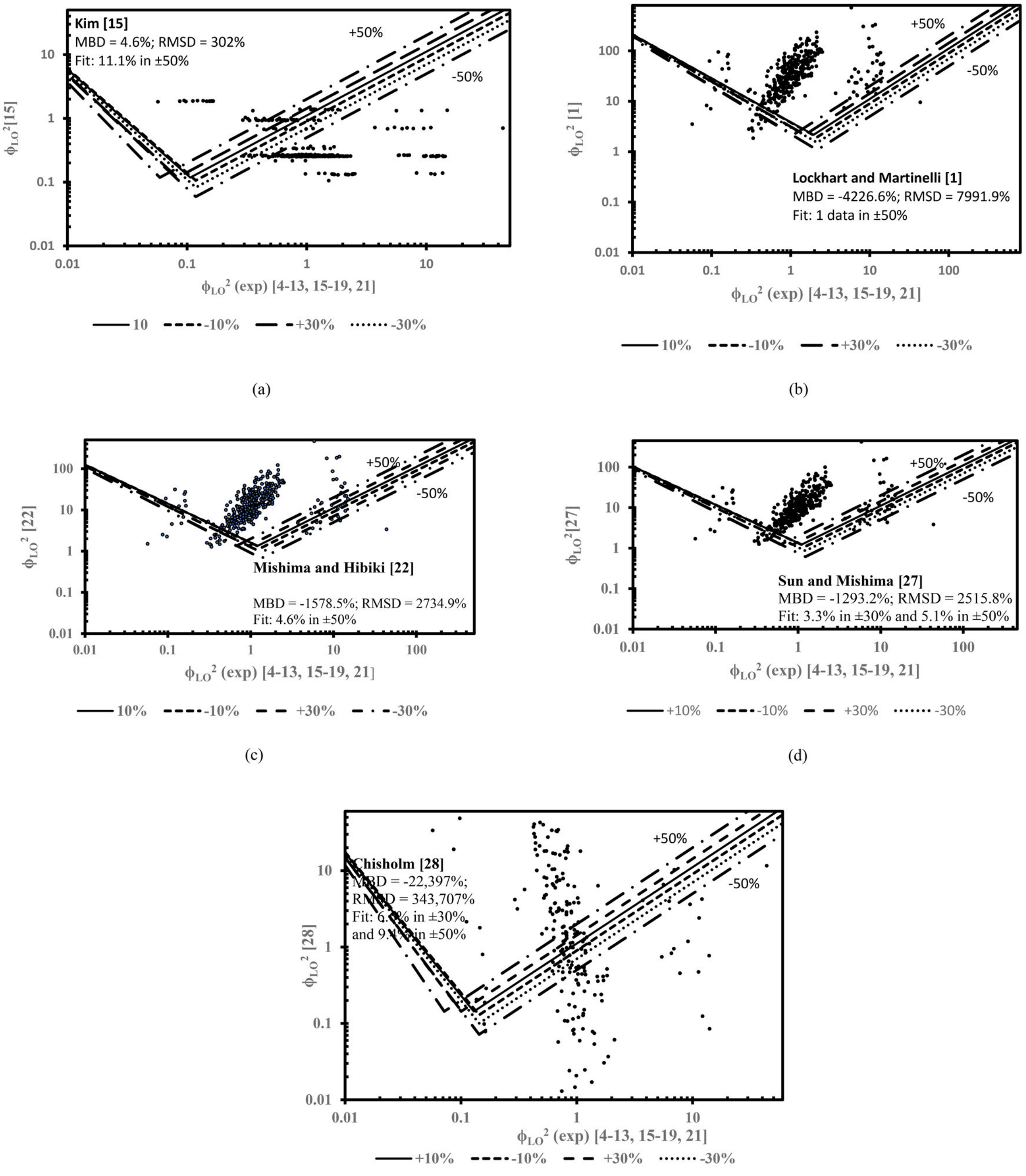


**Figure 7.** Predictive correlation for two-phase multiplier (Eq. (6)) for turbulent condensation in multiport minichannel condensers.



(e)

**Figure 8.** Comparison with widely reported correlations for turbulent condensation pressure drop in multiport minichannels: (a) Kim [15]; (b) Lockhart and Martinelli [1]; (c) Mishima and Hibiki [22]; (d) Sun and Mishima [27]; (e) Chisholm [28].

with the Lockhart and Martinelli [1] equation deploying the turbulent liquid and turbulent vapor flow parameter $X_{turb,\ turb}$. The Lockhart-Martinelli [1] correlation was a poor fit to the compiled data and fit only one data in ±50%. Even with the turbulent liquid and vapor flow Martinelli parameter $X_{turb,\ turb,}$ their correlation was poor at an MBD of −4226.6% and RMSD of 7991.9%. This poor fit could be because of the constant C = 20 in the correlation, which is static and not a variable depending on the liquid-only Reynolds number $Re_{LO}$, the Laplace variable La, or the liquid Weber number $We_L$ deployed by others [22, 23, 27]. Dynamic, flow regime-dependent regression value-based correlations fit the data better than static constant-based equations.

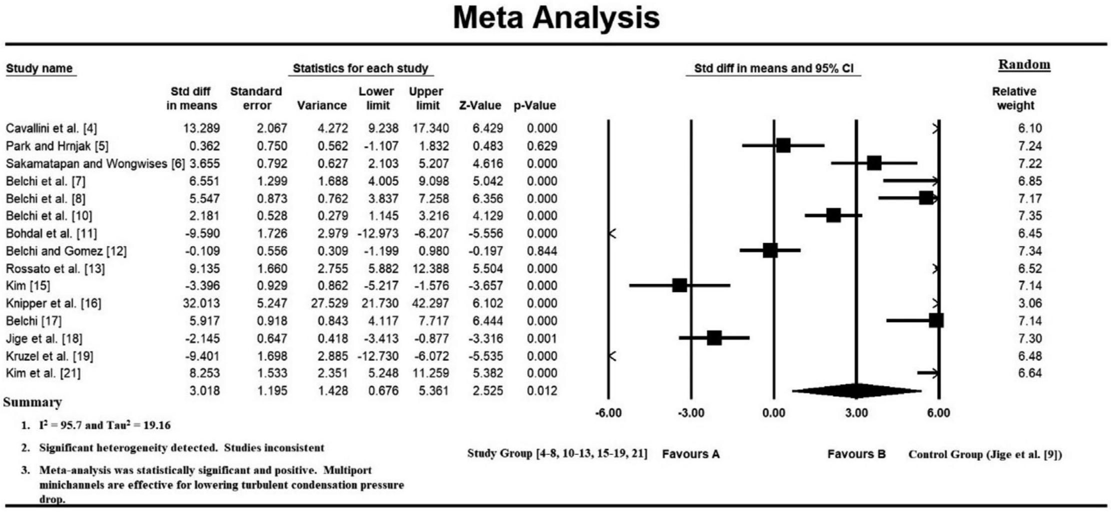
A comparison with the Mishima and Hibiki [22] correlation is shown in Figure 8c. Because of the diameter dependent variable regression constant, the Mishima and Hibiki [22] correlation fit better than the Lockhart and Martinelli [1] correlation. However, their correlation was poor at an MBD of −1578.5% and RSMD of 2734.9%, with only 4.6% of data fitting

**Table 3.** Predictive correlations for turbulent flow condensation pressure drop in multiport minchannels.

| Study | Deviation | | |
|---|---|---|---|
| | MBD | RMSD | Fit |
| Current study (Eq. (6))<br>$\phi_{LO}^2 = 507.76X_{turb,\ \ turb}^{-1.22} d_h^{1.36} x^{-1.1} G^{-0.171} N_{port}^{0.99}$<br>($Re_{LO} = 2301$–15,138, G = 175–1400 kg/m$^2$s, x = 0.009–0.857,<br>$d_h = 0.64$–1.6 mm, and $N_{port} = 4$–37) | −7.1% | 42.8% | 29.1% in ±10%; 68.4% in ±30%; 80.5% in ±50% |
| Kim [15]<br>$\frac{\left(\frac{dP}{dZ}\right)_{TP}}{\left(\frac{dP}{dZ}\right)_{TP,0.95}} = 0.4 d_h^{-3.75} G^{-0.06} x^{0.01} N^{0.22}$<br>$(dP/dZ)_{TP,\ 0.95}$: Condensation friction pressure gradient in a 0.95 mm multiport minichannel<br>($Re_L = 2400$–5200, G = 100–400 kg/m$^2$s, $N_{port} = 9$–18, x = 0.2–0.85,<br>$d_h = 0.78$–0.95 mm) | 4.6% | 302% | 11% in ±50% |
| Lockhart and Martinelli [1]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\ \ turb}} + \frac{1}{X_{turb,\ \ turb}^2}$<br>C = 20 for $Re_{LO} > 2000$ and $Re_v > 2000$<br>(G = 50–1500 kg/m$^2$s, $T_{sat} = 21$–29 °C, $Re_{LO} = 1.5$–124,000 and<br>$Re_v = 7$–86,500) | −4226.6% | 7991.9% | 1 data in ±50% |
| Mishima and Hibiki [22]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\ \ turb}} + \frac{1}{X_{turb,\ \ turb}^2}$<br>C = 21(1-e$^{-0.319d}$) (d in mm)<br>(G = 50–1500 kg/m$^2$s, x = 0–1, $Re_{LO} = 90$–12,204, $Re_v = 5$–12,200<br>and d = 1–4 mm) | −1578.5% | 2734.9% | 4.6% in ±50% |
| Sun and Mishima [27]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\ \ turb}} + \frac{1}{X_{turb,\ \ turb}^2}$<br>$C = 1.79\left(\frac{Re_v}{Re_{LO}}\right)^{0.4}\left(\frac{1-x}{x}\right)^{0.5}$<br>(G = 50–2000 kg/m$^2$s, $Re_{LO} = 10$–37,000, $Re_v = 0$ to $4 \times 10^5$ and x = 0–1 ) | −1293.2% | 2515.8% | 3.3% in ±30%; 5.1% in ±50% |
| Chisholm [28]<br>$\phi_{LO}^2 = 1 + \left(X^2 - 1\right)\left(Bx^{0.875}(1-x)^{0.875} + x^{1.75}\right)$<br>$X = \left(\frac{1-x}{x}\right)^{2-n}\left(\frac{\rho_v}{\rho_L}\right)\left(\frac{\mu_L}{\mu_v}\right)^n$ n = 0.1–0.25<br>$0 < X < 9.5$<br>G < 500 kg/m$^2$s, B = 4.8.<br>500 < G < 1900 kg/m$^2$s, B = 2400/G<br>G > 1900 kg/m$^2$s, B = 55/G$^{0.25}$<br>$9.5 < X < 28$<br>G ≤ 600 kg/m$^2$s, B = 520/(XG$^{0.25}$)<br>G > 600 kg/m$^2$s, B = 21/X<br>$X > 28$<br>B = 15000/(X$^2$G$^{0.5}$)<br>($Re_{LO} = 1.5$–124,000, $Re_v = 7$–86,500, X = 0.1–100, and x = 0.1–0.9). | −22,397% | 343,707% | 6.6% in ±30%; 9.4% in ±50% |

within ±50%. The hydraulic diameter in the Mishima and Hibiki [22] correlation varied exponentially while its exponent was 1.36 in Eq. (6). That over-reliance on the hydraulic diameter without other moderating variables such as the vapor quality x or the number of ports $N_{port}$ may have resulted in the poor fit.

The Sun and Mishima [27] correlation and its evaluation with the compiled data are shown in Figure 8d. The Lockhart and Martinelli [1] regression constant C in the Sun and Mishima [27] correlation was a function of the vapor Reynolds number $Re_V$, the liquid-only Reynolds number $Re_{LO}$ and the vapor quality x. It was more sophisticated than the Lockhart and Martinelli [1] and the Mishima and Hibiki [22] correlations. However, at an MBD of −1293.2% and RSMD of 2515.8%, the Sun and Mishima [27] equation fit only 3.3% of the data within ±30% and 5.1% within ±50%. Although it's an equation based on nearly three thousand data, the Sun and Mishima [27] equation lacked the current data after 2009. This lack of data could have resulted in the poor fit.



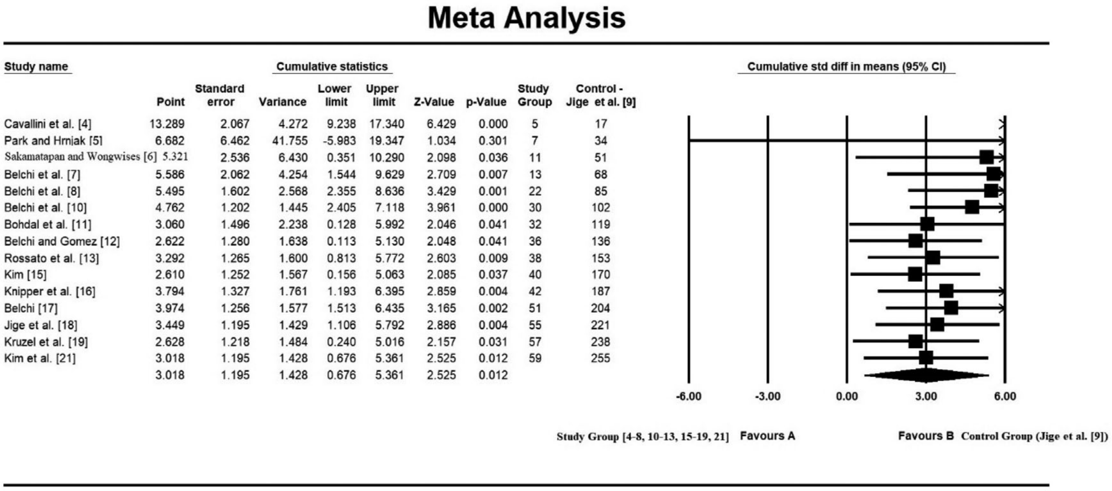
Meta Analysis

| Study name | Statistics for each study | | | | | | | Random |
|---|---|---|---|---|---|---|---|---|
| | Std diff in means | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Relative weight |
| Cavallini et al. [4] | 13.289 | 2.067 | 4.272 | 9.238 | 17.340 | 6.429 | 0.000 | 6.10 |
| Park and Hrnjak [5] | 0.362 | 0.750 | 0.562 | -1.107 | 1.832 | 0.483 | 0.629 | 7.24 |
| Sakamatapan and Wongwises [6] | 3.655 | 0.792 | 0.627 | 2.103 | 5.207 | 4.616 | 0.000 | 7.22 |
| Belchi et al. [7] | 6.551 | 1.299 | 1.688 | 4.005 | 9.098 | 5.042 | 0.000 | 6.85 |
| Belchi et al. [8] | 5.547 | 0.873 | 0.762 | 3.837 | 7.258 | 6.356 | 0.000 | 7.17 |
| Belchi et al. [10] | 2.181 | 0.528 | 0.279 | 1.145 | 3.216 | 4.129 | 0.000 | 7.35 |
| Bohdal et al. [11] | -9.590 | 1.726 | 2.979 | -12.973 | -6.207 | -5.556 | 0.000 | 6.45 |
| Belchi and Gomez [12] | -0.109 | 0.556 | 0.309 | -1.199 | 0.980 | -0.197 | 0.844 | 7.34 |
| Rossato et al. [13] | 9.135 | 1.660 | 2.755 | 5.882 | 12.388 | 5.504 | 0.000 | 6.52 |
| Kim [15] | -3.396 | 0.929 | 0.862 | -5.217 | -1.576 | -3.657 | 0.000 | 7.14 |
| Knipper et al. [16] | 32.013 | 5.247 | 27.529 | 21.730 | 42.297 | 6.102 | 0.000 | 3.06 |
| Belchi [17] | 5.917 | 0.918 | 0.843 | 4.117 | 7.717 | 6.444 | 0.000 | 7.14 |
| Jige et al. [18] | -2.145 | 0.647 | 0.418 | -3.413 | -0.877 | -3.316 | 0.001 | 7.30 |
| Kruzel et al. [19] | -9.401 | 1.698 | 2.885 | -12.730 | -6.072 | -5.535 | 0.000 | 6.48 |
| Kim et al. [21] | 8.253 | 1.533 | 2.351 | 5.248 | 11.259 | 5.382 | 0.000 | 6.64 |
| | 3.018 | 1.195 | 1.428 | 0.676 | 5.361 | 2.525 | 0.012 | |

**Summary**

1. **$I^2 = 95.7$ and $Tau^2 = 19.16$**
2. **Significant heterogeneity detected. Studies inconsistent**
3. **Meta-analysis was statistically significant and positive. Multiport minichannels are effective for lowering turbulent condensation pressure drop.**

**Figure 9.** Meta-analysis of turbulent condensation pressure drop [4–13, 15–19, 21] in multiport minichannels at $Re_{LO} = 2436$.



Meta Analysis

| Study name | Cumulative statistics | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Point | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Study Group | Control - Jige et al. [9] |
| Cavallini et al. [4] | 13.289 | 2.067 | 4.272 | 9.238 | 17.340 | 6.429 | 0.000 | 5 | 17 |
| Park and Hrnjak [5] | 6.682 | 6.462 | 41.755 | -5.983 | 19.347 | 1.034 | 0.301 | 7 | 34 |
| Sakamatapan and Wongwises [6] | 5.321 | 2.536 | 6.430 | 0.351 | 10.290 | 2.098 | 0.036 | 11 | 51 |
| Belchi et al. [7] | 5.586 | 2.062 | 4.254 | 1.544 | 9.629 | 2.709 | 0.007 | 13 | 68 |
| Belchi et al. [8] | 5.495 | 1.602 | 2.568 | 2.355 | 8.636 | 3.429 | 0.001 | 22 | 85 |
| Belchi et al. [10] | 4.762 | 1.202 | 1.445 | 2.405 | 7.118 | 3.961 | 0.000 | 30 | 102 |
| Bohdal et al. [11] | 3.060 | 1.496 | 2.238 | 0.128 | 5.992 | 2.046 | 0.041 | 32 | 119 |
| Belchi and Gomez [12] | 2.622 | 1.280 | 1.638 | 0.113 | 5.130 | 2.048 | 0.041 | 36 | 136 |
| Rossato et al. [13] | 3.292 | 1.265 | 1.600 | 0.813 | 5.772 | 2.603 | 0.009 | 38 | 153 |
| Kim [15] | 2.610 | 1.252 | 1.567 | 0.156 | 5.063 | 2.085 | 0.037 | 40 | 170 |
| Knipper et al. [16] | 3.794 | 1.327 | 1.761 | 1.193 | 6.395 | 2.859 | 0.004 | 42 | 187 |
| Belchi [17] | 3.974 | 1.256 | 1.577 | 1.513 | 6.435 | 3.165 | 0.002 | 51 | 204 |
| Jige et al. [18] | 3.449 | 1.195 | 1.429 | 1.106 | 5.792 | 2.886 | 0.004 | 55 | 221 |
| Kruzel et al. [19] | 2.628 | 1.218 | 1.484 | 0.240 | 5.016 | 2.157 | 0.031 | 57 | 238 |
| Kim et al. [21] | 3.018 | 1.195 | 1.428 | 0.676 | 5.361 | 2.525 | 0.012 | 59 | 255 |
| | 3.018 | 1.195 | 1.428 | 0.676 | 5.361 | 2.525 | 0.012 | | |

**Figure 10.** Cumulative meta-analysis of turbulent condensation pressure drop [4–13, 15–19, 21] in multiport minichannels.

The widely reported Chisholm [28] correlation was also compared with the compiled data. The sophisticated correlation for two-phase friction pressure gradient in smooth tubes and channels fit 6.6% of the gathered data within ±30% and 9.4% within ±50%. As shown in Figure 8e, at an MBD of −22,397% and RMSD of 343,707%, it was a poor fit than Eq. (6). The absence of a phase-change parameter like the Martinelli parameter for turbulent liquid-vapor flow $X_{turb,\ turb}$ may have resulted in the poor prediction of the two-phase flow regime and overall poor fit to the data.

All the predictive correlations for estimating the two-phase multiplier during turbulent condensation in multiport minichannels are shown in Table 3 [1, 15, 22, 27, 28].

## Meta-analysis of turbulent condensation pressure drop in multiport minichannel condensers

Meta-analysis was conducted on the compiled studies [4–13, 15–19, 21] to assess the reliability of the turbulent condensation pressure drop database. To account for all the variables involved, the control variable was chosen as $X_{turb,\ turb}^{-1.22} d_h^{1.36} x^{-1.1} G^{-0.171} N^{0.99}$. Because it was the single most extensive study, the Jige et al. [9] study was chosen as the control group while the others [4–8, 10–13, 15–19, 21] were the study group.

A Forest plot of the meta-analysis at an average control variable of 0.002 and a corresponding liquid-only Reynolds number of $Re_{LO} = 2436$ is shown in Figure 9. Except for the Park and Hrnjak [5] and Belchi and Gomez [12] studies, the 95% CI bands of the other studies did not cross the null (0) line,

**Table 4.** Multiport minichannel evaporator pressure drop data.

| Study | Fluid | No. of data<br>Laminar | Turbulent | % Of data | Experimental uncertainty |
|---|---|---|---|---|---|
| Yun et al. [29] | R410A | 15 | 3 | 2.76% | Not available |
| Kaew-On and Wongwises [30] | R134a | 15 | 0 | 5.79% | Not available |
| Rivera et al. [31] | R32 and R134a | 42 | 34 | 11.3% | ±3.3% |
| Rahman et al. [32] | R134a | 43 | 0 | 6.21% | ±0.5% |
| Chien et al. [33] | R410A | 121 | 0 | 16.83% | ±5% |
| Gao et al. [34] | R134a | 10 | 0 | 2.21% | ±0.2% |
| Jige et al. [35] | R32 and R1234Ze(E) | 64 | 1 | 11.86% | ±2% |
| Chien et al. [36] | R290 and R717 | 70 | 1 | 10.62% | Not available |
| Jige et al. [37] | R1234yf and R32 mixture | 121 | 0 | 19.17% | ±3% |
| Klugmann et al. [38] | Ethanol | 36 | 0 | 6.21% | ±0.14% |
| Nguyen et al. [39] | R410A | 47 | 0 | 7.03% | ±0.2% |

indicating that the data compiled from the other studies [4, 6–11, 13, 15–19, 21] are statistically significant and relevant.

The result depicted by the cumulative diamond at the bottom suggests a statistically significant and positive analysis. The development of the random model-based analysis lying between the lower and upper limits of 0.676 and 5.361 strongly indicates that multiport minichannels are effective interventions for lowering the condensation pressure drop for turbulent flows. Despite the considerable inconsistency and heterogeneity detected in the studies, $I^2 = 95.7$ and $Tau^2 = 19.1$, multiport minichannels for reducing the condensation pressure drop in turbulent flows are statistically positive and strongly recommended. The cumulative meta-analysis of the compiled studies is shown in Figure 10.

## Multiport minichannel evaporators

Multiport minichannels have also been widely deployed as evaporators. Light-weight, compact, and highly efficient minichannel-based evaporators offer cost-effective alternatives to the cumbersome shell and tube boilers.

Yun et al. [29] reported an experimental friction pressure drop for the evaporation of R410A in two multiport minichannel evaporators. The friction pressure gradient measured in the 1.36 mm and 1.44 mm diameter multiport minichannel evaporators was reduced to a two-phase multiplier and was successfully compared with published correlations. No new correlations were reported. Experiments were conducted in the mass flux range of $G = 200–400\,kg/m^2s$, saturation temperature $T_{sat} = 5–10\,°C$, and vapor quality $x = 0.2–0.8$.

Kaew-On and Wongwises [30] measured the friction pressure drop during the evaporation of R134a in a multiport minichannel evaporator. They modified the regression constant C in the Lockhart and Martinelli [1] equation and reported satisfactory agreement with widely published correlations. It was reported that the boiling heat flux $q''$ had little impact on the friction pressure drop. Evaporation pressure drop measurements were made at a mass flux of $G = 77–155\,kg/m^2s$, saturation temperature $T_{sat} = 31.3\,°C$ and vapor quality $x = 0.3–0.9$.

Rivera et al. [31] investigated the evaporation of R134a and R32 in two multiport minichannel evaporators. The friction pressure drop data was successfully compared with widely reported correlations. No new correlations were proposed. The friction pressure gradient decreased with saturation pressure. Experiments were conducted at a saturation temperature $T_{sat} = 7.5–12.5\,°C$, mass flux $G = 480–1320\,kg/m^2s$, and vapor quality $x = 0.1–0.5$.

Rahman et al. [32] reported friction pressure drop for evaporation of R134a in a 0.81 mm diameter multiport minichannel evaporators with and without internal grooves. The friction pressure gradient increased with decreasing hydraulic diameter and decreased with saturation pressure. No new correlations were reported. The evaporation friction pressure gradient was measured at a mass flux $G = 50–200\,kg/m^2s$, saturation temperature $T_{sat} = 30\,°C$, and vapor quality $x = 0.1–0.9$.

Chien et al. [33] measured the friction pressure drop for evaporation of R410A in several multiport minichannels with hydraulic diameters ranging from 0.96 to 1.16 mm. The boiling heat flux $q''$ had no impact on the friction pressure gradient, which increased with the mass velocity G and the vapor quality x. No new correlations were reported. Experiments were conducted at a mass flux of $G = 50–150\,kg/m^2s$, saturation temperature $T_{sat} = 6\,°C$, and vapor quality $x = 0.1–1.0$.

Gao et al. [34] reported friction pressure drop for evaporation of R134a in a 0.69 mm diameter open-cell metal foam multiport minichannel evaporator. Of the three major components of the total pressure drop, i.e., acceleration, friction, and hydrostatic, friction pressure drop contributed more than 70% of the

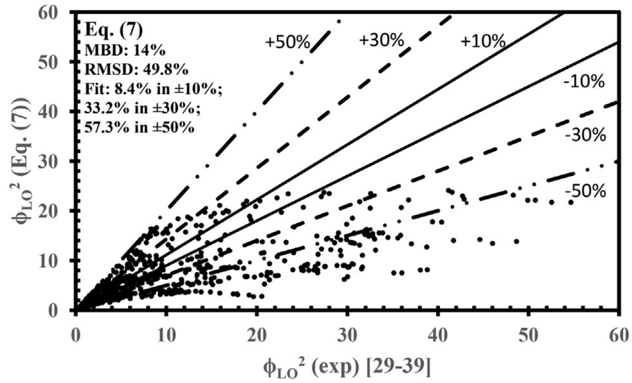
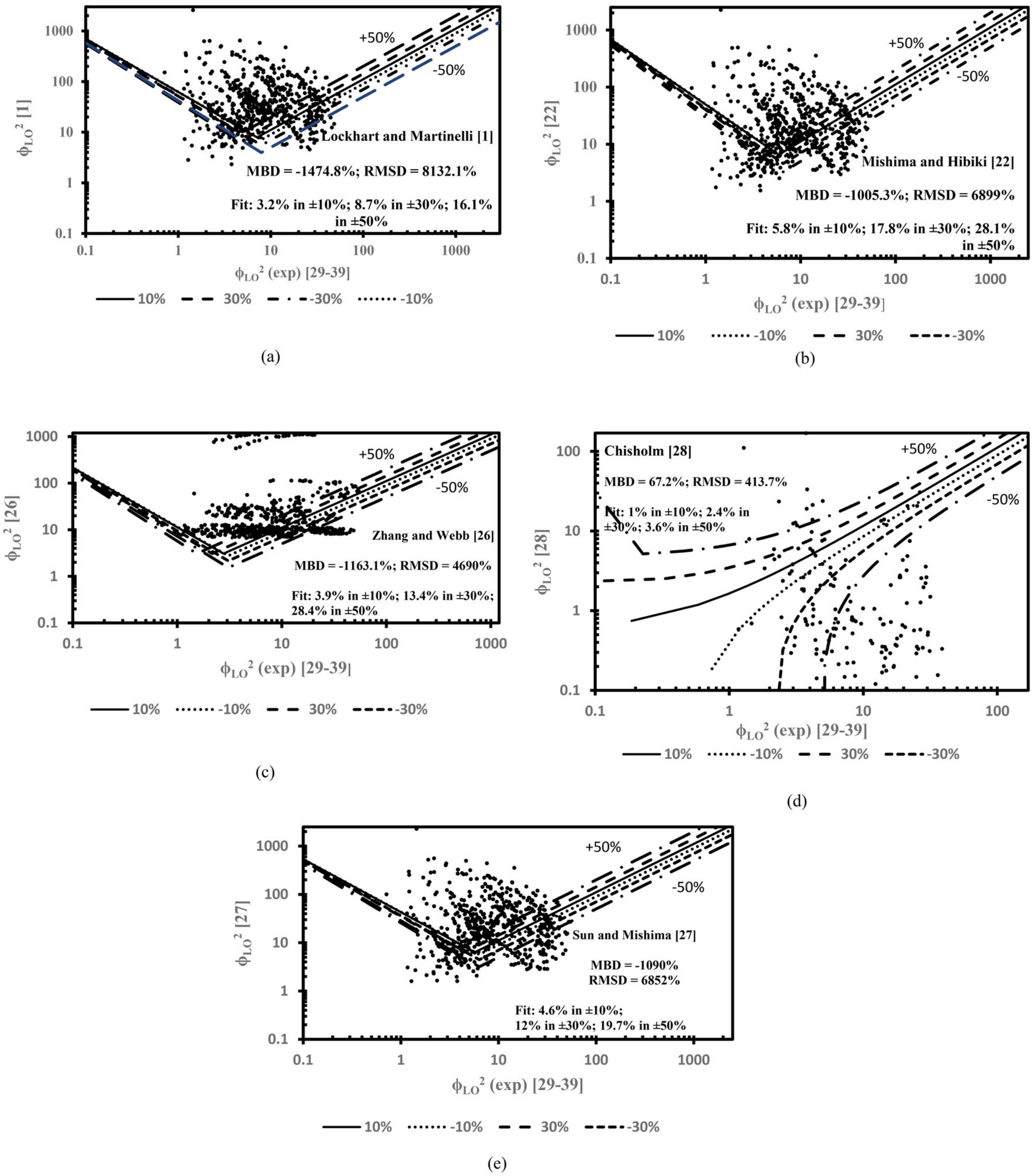


**Figure 11.** Predictive correlation (Eq. (7)) for laminar pressure drop in multiport minichannel evaporators.

overall pressure drop. A new evaporation friction factor correlation was proposed. The evaporation pressure drop experiments were conducted at a mass flux of $G = 350–700\,kg/m^2s$, saturation temperature $T_{sat} = 29\,°C$, and vapor quality $x = 0.1–0.9$.

Jige et al. [35] conducted flow boiling experiments with R32 and R1234ze(E) in a 0.82 mm diameter multiport minichannel evaporator. The friction pressure drop of R32 was lower than that of R1234ze(E). No new friction pressure drop correlations were proposed. The experiments were conducted at mass flux of $G = 50–400\,kg/m^2s$, saturation temperature $T_{sat} = 15\,°C$, and vapor quality $x = 0.1–1.0$.



(a)

(b)

(c)

(d)

(e)

**Figure 12.** Comparison with widely reported correlations for laminar evaporation pressure drop in multiport minichannels: (a) Lockhart and Martinelli [1]; (b) Mishima and Hibiki [22]; (c) Zhang and Webb [26]; (d) Chisholm [28]; (e) Sun and Mishima [27].

**Table 5.** Predictive correlations for laminar flow evaporation pressure drop in multiport minichannels.

| Study | Deviation | | |
|---|---|---|---|
| | MBD | RMSD | Fit |
| Current study (Eq. (7))<br>$\phi_{LO}^2 = 15.49\mathrm{X}_{lam,\ \ turb}^{0.54} Re_{LO}^{0.36} Bo^{0.06} x^{0.93} N_{port}^{-1.21} P_r^{-0.84} \left(\frac{\mu_L}{\mu_v}\right)^{0.12} T_r^{-1.13}$<br>(G = 50–1020 kg/m$^2$s, q″ = 3–21 kW/m$^2$, x = 0–1, Re$_{LO}$ = 2–2278,<br>Bo = (1–20,000) × 10$^5$, P$_r$ = 0.012–0.24,<br>T$_r$ = 0.74–1.3, N$_{port}$ = 7–50, ($\mu_L/\mu_v$) = 10.36–67.39 ) | 14% | 49.8% | 8.4% in ±10%; 33.2% in ±30%; 57.3% in ±50% |
| Lockhart and Martinelli [1]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>C = 12 for Re$_{LO}$ < 2000 and Re$_v$ > 2000<br>(G = 50–1500 kg/m$^2$s, T$_{sat}$ = 21–29 °C, Re$_{LO}$ = 1.5–124,000 and<br>Re$_v$ = 7–86,500) | –1475% | 8132% | 3.2% in ±10%; 8.7% in ±30%; 16.1% in ±50% |
| Mishima and Hibiki [22]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>C = 21(1-e$^{-0.319d}$) (d in mm)<br>(G = 50–1500 kg/m$^2$s, x = 0–1, Re$_{LO}$ = 90–12,204, Re$_v$ = 5–12,200<br>and d = 1–4 mm) | −1005% | 6899% | 5.8% in ±10%; 17.8% in ±30%; 28.1% in ±50% |
| Zhang and Webb [26]<br>$\phi_{LO}^2 = (1-x)^2 + \frac{2.87x^2}{P_r} + 1.68x^{0.25}(1-x)^2 P_r^{-1.64}$<br>(G = 200–1000 kg/m$^2$s, T$_{sat}$ = 20–65 °C, Re$_{LO}$ < 2300, P$_r$ = 0.25–0.51, and<br>x = 0.17–0.93) | −1163% | 4690% | 3.9% in ±10%; 13.4% in ±30%; 28.4% in ±50% |
| Chisholm [28]<br>$\phi_{LO}^2 = 1 + (\mathrm{X}^2 - 1)\left(Bx^{0.875}(1-x)^{0.875} + x^{1.75}\right)$<br>$\mathrm{X} = \left(\frac{1-x}{x}\right)^{2-n}\left(\frac{\rho_v}{\rho_L}\right)\left(\frac{\mu_L}{\mu_v}\right)^n \mathrm{n} = 0.1 - 0.25\ 0 < \mathrm{X} < 9.5$<br>G < 500 kg/m$^2$s, B = 4.8.<br>500 < G < 1900 kg/m$^2$s, B = 2400/G<br>G > 1900 kg/m$^2$s, B = 55/G$^{0.25}$<br>9.5 < X < 28<br>G ≤ 600 kg/m$^2$s, B = 520/(XG$^{0.25}$)<br>G > 600 kg/m$^2$s, B = 21/X<br>X > 28<br>B = 15000/(X$^2$G$^{0.5}$)<br>(Re$_{LO}$ = 1.5–124,000, Re$_v$ = 7–86,500, X = 0.1–100, and x = 0.1–0.9). | 67.2% | 413.7% | 1% in ±10%; 2.4% in ±30%; 3.6% in ±50% |
| Sun and Mishima [27]<br>$\phi_{LO}^2 = 1 + \frac{C}{\mathrm{X}_{lam,\ \ turb}} + \frac{1}{\mathrm{X}_{lam,\ \ turb}^2}$<br>$C = 1.79\left(\frac{Re_v}{Re_{LO}}\right)^{0.4}\left(\frac{1-x}{x}\right)^{0.5}$<br>(G = 50–2000 kg/m$^2$s, Re$_{LO}$ = 10–37,000, Re$_v$ = 0 to 4 × 10$^5$ and x = 0–1) | −1090% | 6852% | 4.6% in ±10%; 12% in ±30%; 19.7% in ±50% |

Chien et al. [36] reported the evaporation friction pressure drop for R-717 and R-290 in a 0.83 mm diameter multiport minichannel evaporator. Like other studies, the measured friction pressure drop was the major component of the total pressure drop. No new correlations were reported. The evaporation pressure gradient was measured at a mass flux of G = 50–500 kg/m$^2$s, saturation temperature T$_{sat}$ = 6 °C, and vapor quality x = 0.1–1.0.

Jige et al. [37] reported the friction pressure drop for the evaporation of R1234yf and R32 mixtures in a 0.82 mm diameter multiport minichannel evaporator. The friction pressure drop increased with the concentration of R1234yf. The pressure drop data was successfully compared with widely reported correlations. No new correlations were reported. Experiments were conducted at a mass flux of G = 50–400 kg/m$^2$s, and vapor quality x = 0.1–1.0.

Klugmann et al. [38] conducted pressure drop measurements during the evaporation of Ethanol in two multiport minichannel evaporators 0.5 mm and 1 mm in diameter. Variations in the friction pressure drop with the mass velocity were minimal. A minigap evaporator was also tested, and the friction pressure drop for identical mass velocity and vapor quality was modestly lower than that in a multiport minichannel. The experiments were conducted at a mass flux of $G = 51\,\mathrm{kg/m^2s}$, saturation temperature $T_{sat} = 71\,°C$, and vapor quality $x = 0.1–0.9$.

Nguyen et al. [39] reported an evaporation pressure drop of R410A in a 1.14 mm and 1.16 mm diameter multiport minichannel evaporator. No appreciable variation was detected in the measured friction pressure drop with heat flux. Higher mass velocities increased the interfacial liquid-vapor shear, which increased the friction pressure drop. No new correlations were reported. The evaporation pressure gradient was measured at a mass flux $G = 50–150\,\mathrm{kg/m^2s}$, saturation temperature $T_{sat} = 6\,°C$ and vapor quality $x = 0.1–0.9$.

Only one correlation [34] had been proposed for estimating the friction pressure drop in evaporating flows in multiport minichannels in the past two decades. Therefore, updating the database and suggesting a universal correlation for predicting the friction pressure drop in multiport minichannel evaporators is necessary. In their recent article [40], the authors analyzed the local heat transfer data in multiport minichannel evaporators. This article complements that work with regression and meta-analysis of friction pressure gradient and a new correlation for the two-phase multiplier for multiport minichannel evaporators.

All the friction pressure drop data compiled from multiport minichannel evaporators are shown in Table 4 [29–39].

## Laminar evaporation pressure drop: Regression analysis and correlation development

The laminar evaporation pressure drop data from eleven sources [29–39] were analyzed using regression models such as ANOVA, power-law, log-linear, linear, neural networks, cubic spline, etc. As shown in Figure 11, at an MBD of 14% and RMSD of 49.8%, the power-law equation Eq. (7) best fits the compiled data. Equation (7) fit 8.4% of the data within 10%, 33.2% within ±30%, and 57.3% within ±50%. The reduced pressure $P_r$ and temperature $T_r$ were deployed along with the boiling parameter Bo.

Equation (7) which is based on the laminar liquid and turbulent vapor flow Martinelli parameter $X_{\mathrm{lam,\ turb}}$ is valid for the liquid-only Reynolds number $Re_{LO} = 2–2278$, reduced pressure $P_r = 0.012–0.24$, reduced temperature $T_r = 0.74–1.3$, number of parallel ports $N_{port} = 7–50$, boiling parameter $Bo = (1–20{,}000) \times 10^{-7}$, and viscosity ratio $(\mu_L/\mu_v) = 10.36–67.39$.

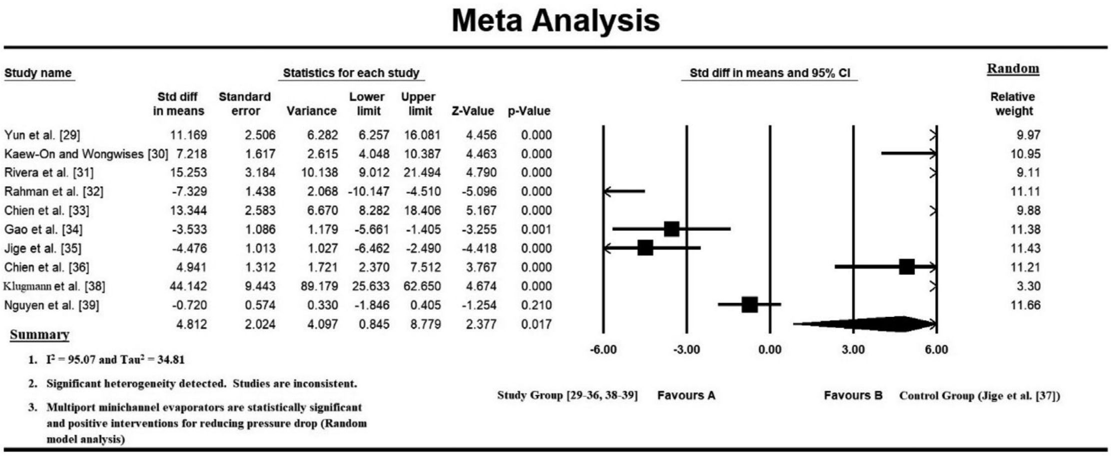
$$\phi_{LO}^2 = 15.49 X_{lam,\ turb}^{0.54} Re_{LO}^{0.36} Bo^{0.06} x^{0.93} N^{-1.21} P_r^{-0.84} \left(\frac{\mu_L}{\mu_v}\right)^{0.12} T_r^{-1.13} \tag{7}$$

Widely reported correlations for predicting the two-phase multiplier were evaluated with the compiled data. The Lockhart and Martinelli [1] correlation overpredicted the bulk of the data. As shown in Figure 12a, at an MBD of −1474.8% and RMSD of 8132.1%, the Lockhart and Martinelli [1] correlation fit 3.2% of the data within ±10%, 8.7% in ±30%, and 16.1% in ±50%. The lack of the boiling parameter Bo and a static constant C in their correlation may have been the reason for the average fit.

As shown in Figure 12b, the Mishima and Hibiki [22] correlation was marginally better than the Lockhart and Martinelli [1] correlation. At an MBD of −1005.3% and RSMD of 6899%, the Mishima and Hibiki [22] correlation fit 5.8% of the data within ±10%, 17.8% within ±30%, and 28.1% in ±50%. The Mishima and Hibiki [22] correlation modified the regression constant in the Lockhart and Martinelli [1] equation with an exponential function of the hydraulic diameter. Despite that modification, the Mishima and Hibiki [22] correlation still lacked the boiling parameter or the Weber number We to model the nucleate boiling phase of the evaporation, which may have resulted in the mediocre fit to the data.

A comparison with the Zhang and Webb [26] correlation is shown in Figure 12c. At an MBD of −1163.1% and RSMD of 4690.3%, the Zhang and Webb [26] correlation was a slightly better fit than the Mishima and Hibiki [22] correlation. It fit 3.94% of the data within ±10%, 13.4% in ±30%, and 28.4% within ±50%. The reduced pressure and vapor quality in the Zhang and Webb [26] correlation accurately predict the saturation condition and local vapor quality. The accuracy of the saturation conditions may have improved the fit compared to the Mishima and Hibiki [22] correlation.

The widely reported Chisholm [28] correlation was evaluated with the compiled data in Figure 12d. At an MBD of 67.2% and RSMD of 413.7%, the Chisholm [28] correlation fit 1% of the data within ±10%, 2.4% in ±30%, and 3.6% within ±50%. The poor fit despite



Meta Analysis

| Study name | Std diff in means | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Relative weight |
|---|---|---|---|---|---|---|---|---|
| Yun et al. [29] | 11.169 | 2.506 | 6.282 | 6.257 | 16.081 | 4.456 | 0.000 | 9.97 |
| Kaew-On and Wongwises [30] | 7.218 | 1.617 | 2.615 | 4.048 | 10.387 | 4.463 | 0.000 | 10.95 |
| Rivera et al. [31] | 15.253 | 3.184 | 10.138 | 9.012 | 21.494 | 4.790 | 0.000 | 9.11 |
| Rahman et al. [32] | -7.329 | 1.438 | 2.068 | -10.147 | -4.510 | -5.096 | 0.000 | 11.11 |
| Chien et al. [33] | 13.344 | 2.583 | 6.670 | 8.282 | 18.406 | 5.167 | 0.000 | 9.88 |
| Gao et al. [34] | -3.533 | 1.086 | 1.179 | -5.661 | -1.405 | -3.255 | 0.001 | 11.38 |
| Jige et al. [35] | -4.476 | 1.013 | 1.027 | -6.462 | -2.490 | -4.418 | 0.000 | 11.43 |
| Chien et al. [36] | 4.941 | 1.312 | 1.721 | 2.370 | 7.512 | 3.767 | 0.000 | 11.21 |
| Klugmann et al. [38] | 44.142 | 9.443 | 89.179 | 25.633 | 62.650 | 4.674 | 0.000 | 3.30 |
| Nguyen et al. [39] | -0.720 | 0.574 | 0.330 | -1.846 | 0.405 | -1.254 | 0.210 | 11.66 |
| Summary | 4.812 | 2.024 | 4.097 | 0.845 | 8.779 | 2.377 | 0.017 | |

1. $I^2 = 95.07$ and $Tau^2 = 34.81$
2. Significant heterogeneity detected. Studies are inconsistent.
3. Multiport minichannel evaporators are statistically significant and positive interventions for reducing pressure drop (Random model analysis)

**Figure 13.** Meta-analysis of laminar pressure drop [29–39] in multiport minichannel evaporators.

the reasonable MBD was probably due to the wide range of the MBD varying from −8482% to 157%. This may have lowered the MBD value, not guaranteeing a satisfactory fit. Although the Martinelli parameter was modeled accurately, the Chisholm [28] equation lacks the boiling parameter Bo and the Weber number We to accurately model nucleate boiling in the multiport minichannel evaporator. Just as with the Zhang and Webb [26] correlation, this may have resulted in the significant underprediction of the data.

The Sun and Mishima [27] correlation and its evaluation with the compiled data are shown in Figure 12e. At an MBD of −1090% and RMSD of 6852%, the Sun and Mishima [27] correlation fit 4.6% of the data within ±10%, 12% within ±30%, and 19.7% within ±50%. Despite modifying the regression constant C in the Lockhart and Martinelli [1] equation with the Laplace variable La that modeled nucleation and pool boiling accurately, their correlation was only a modest fit to the data. The Sun and Mishima [27] correlation is based on data up to 2009. The lack of recent data in its empirical database and relying on the Lockhart and Martinelli [1] model instead of a power-law model may have contributed to the poor fit.

All the correlations discussed in this section and their validity are given in Table 5 [1, 22, 26–28].

## Meta-analysis of laminar evaporation pressure drop in multiport minichannel evaporators

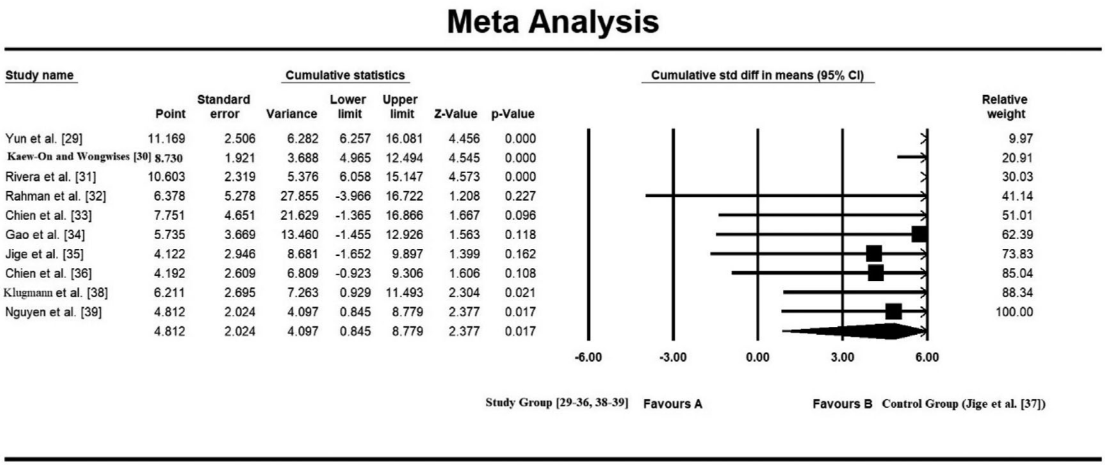
The compiled data [29–39] were also meta-analyzed with the CMA software for inconsistency, publication bias, heterogeneity, and other statistical anomalies. The control variable was set as $X_{lam,\ turb}^{0.54} Re_{LO}^{0.36} Bo^{0.06} x^{0.93} N^{-1.21} P_r^{-0.84} \left(\frac{\mu_L}{\mu_v}\right)^{0.12} T_r^{-1.13}$. Because of the maximum data at the average control variable of 0.68 and liquid-only Reynolds number $Re_{LO} = 722$, the Jige et al. [37] study was chosen as the control group. Meta-analysis of the study group [29–36, 38, 39] and the control group [37] is shown in Figure 13.

Except for the Nguyen et al. [39] study, the 95% CI bands of the remaining studies did not cross the null (0) line. This indicates that their measurements' true mean friction pressure drop doesn't lie in the CI bands and is statistically significant. The cumulative diamond of the random model-based meta-analysis extends between the upper and lower limits of 0.85 and 8.78. This indicates that the meta-analysis is statistically significant and positive and that multiport minichannel evaporators are highly recommended for lowering the pressure drop for laminar flows.

An $I^2$ value of 95 and a corresponding $Tau^2$ value of 34.8 indicate considerable heterogeneity and inconsistency in the compiled data. Consequently, different studies investigating laminar pressure drop in multiport minichannel evaporators under near-identical conditions produced different results while similar results were expected. However, the cumulative analysis of all the studies shown in Figure 14 strongly recommends multiport minichannel evaporators to lower the friction pressure drop for laminar evaporating flows. Because of its weightage, the cumulative 95% CI bands favor the Jige et al. [37] study.

## Turbulent evaporation pressure drop: Regression analysis and correlation development

Limited turbulent pressure drop data were also garnered from the compiled studies [29, 31, 35, 36] and analyzed with various regression models. The power-



| Study name | Point | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Relative weight |
|---|---|---|---|---|---|---|---|---|
| Yun et al. [29] | 11.169 | 2.506 | 6.282 | 6.257 | 16.081 | 4.456 | 0.000 | 9.97 |
| Kaew-On and Wongwises [30] | 8.730 | 1.921 | 3.688 | 4.965 | 12.494 | 4.545 | 0.000 | 20.91 |
| Rivera et al. [31] | 10.603 | 2.319 | 5.376 | 6.058 | 15.147 | 4.573 | 0.000 | 30.03 |
| Rahman et al. [32] | 6.378 | 5.278 | 27.855 | -3.966 | 16.722 | 1.208 | 0.227 | 41.14 |
| Chien et al. [33] | 7.751 | 4.651 | 21.629 | -1.365 | 16.866 | 1.667 | 0.096 | 51.01 |
| Gao et al. [34] | 5.735 | 3.669 | 13.460 | -1.455 | 12.926 | 1.563 | 0.118 | 62.39 |
| Jige et al. [35] | 4.122 | 2.946 | 8.681 | -1.652 | 9.897 | 1.399 | 0.162 | 73.83 |
| Chien et al. [36] | 4.192 | 2.609 | 6.809 | -0.923 | 9.306 | 1.606 | 0.108 | 85.04 |
| Klugmann et al. [38] | 6.211 | 2.695 | 7.263 | 0.929 | 11.493 | 2.304 | 0.021 | 88.34 |
| Nguyen et al. [39] | 4.812 | 2.024 | 4.097 | 0.845 | 8.779 | 2.377 | 0.017 | 100.00 |
|  | 4.812 | 2.024 | 4.097 | 0.845 | 8.779 | 2.377 | 0.017 |  |

**Figure 14.** Cumulative meta-analysis of laminar pressure drop [29–39] in multiport minichannel evaporators.

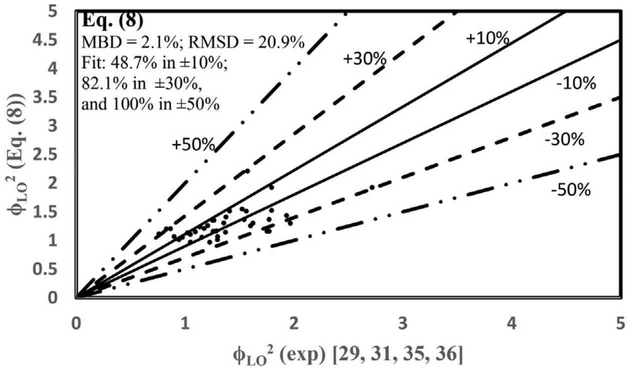


**Figure 15.** Correlation (Eq. (8)) for predicting laminar pressure drop in multiport minichannel evaporators.

law based Eq. (8) is valid for the liquid-only Reynolds number $Re_{LO} = 2330–5450$, boiling parameter $Bo = (0.01–23) \times 10^{-7}$, and Weber number $We = 0.39–0.094$.

$$\phi^2_{LO} = 3.08Bo^{0.19}We^{-0.42} \tag{8}$$

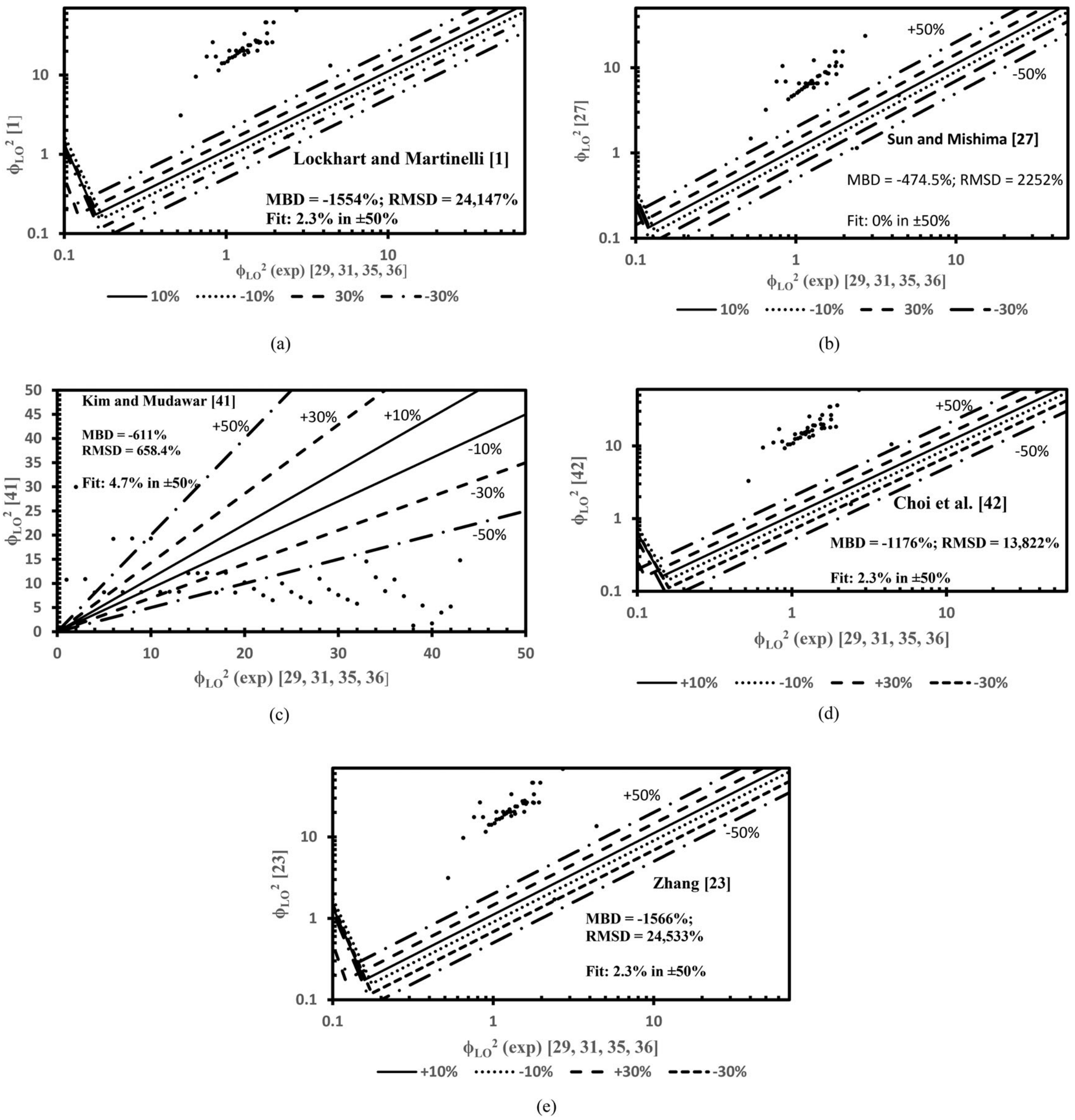
As shown in Figure 15, Eq. (8) fit 48.7% of the data within ±10%, 82.1% within ±30%, and 100% within ±50% at an MBD of 2.1% and RMSD of 20.9%. The boiling parameter Bo accounts for convective boiling while the Weber number We modeled nucleate boiling.

The data were also evaluated with widely reported correlations. A comparison with the Lockhart and Martinelli [1] equation is shown in Figure 16a. At an MBD of −1554% and RMSD of 24,147%, the Lockhart and Martinelli [1] correlation fits a mere 2.3% of the data within ±50%. Their correlation is based on a static regression constant C that doesn't change with the local liquid-only Reynolds number $Re_{LO}$ and is based on two-component liquid and vapor flow data without any evaporation or phase change. These factors may have resulted in the poor fit.

Evaluation of the Sun and Mishima [27] correlation with the compiled data is shown in Figure 16b. At an MBD of −474.5% and RMSD of 2252%, the Sun and Mishima [27] correlation fit none of the compiled data within ±50%. The liquid and vapor Reynolds numbers $Re_L$, $Re_v$, and vapor quality-based regression constant may have improved the fit. However, the lack of evaporation parameters such as the boiling parameter Bo or the Weber number We may have resulted in the poor fit.

A comparison with the Kim and Mudawar [41] correlation is shown in Figure 16c. At an MBD of −611% and RSMD of 658.4%, the Kim and Mudawar [41] correlation fit 4.7% of the data within ±50%. Their correlation modified the regression constant in the Lockhart and Martinelli [1] correlation with the vapor Suratman number $Su_v$, which improves the Weber number We and models nucleation and pool boiling in minichannels more accurately. Their comprehensive database includes data from 2012 and is based on friction pressure drop measurements in single mini and microchannels. The lack of current data and measurements in multiport minichannels, which involve inlet and exit header losses and flow maldistribution, may have resulted in the poor fit.

The compiled data was also evaluated with the Choi et al. [42] correlation in Figure 16d. At an MBD of −1175.7% and RMSD of 13,821.6%, the Choi et al. [42] correlation fit 2.3% of the data within ±50%. Their correlation modified the Lockhart and Martinelli [1] constant with the two-phase Reynolds number $Re_{TP}$ and Weber number $We_{TP}$ and modeled its variation more accurately with the local flow regime. However, their data was based on just one refrigerant, R410A, and this



(a)

(b)

(c)

(d)

(e)

**Figure 16.** Comparison with widely reported correlations for turbulent evaporation pressure drop in multiport minichannels: (a) Lockhart and Martinelli [1]; (b) Sun and Mishima [27]; (c) Kim and Mudawar [41] (d) Choi et al. [42]; (e) Zhang [23].

may have resulted in the poor fit to the compiled data based on several evaporating refrigerants.

The Zhang [23] correlation was compared with the compiled data in Figure 16e. The Lockhart and Martinelli [1] correlation was modified with the Laplace parameter La in the Zhang [23] correlation. At an MBD of −1566.3% and RMSD of 24,533%, the Zhang [23] correlation fit 2.3% of the data within ±50%. Although the Laplace parameter La models nucleate boiling accurately, the Zhang [23] correlation is based on limited data from single minichannels, which may be the reason for the poor fit to the detailed evaporation data from multiport minichannels.

All the correlations discussed in this section and their validity are shown in Table 6 [1, 23, 27, 41, 42].

## Meta-analysis of turbulent evaporation pressure drop in multiport minichannel evaporators

A meta-analysis was performed on the few turbulent pressure drop data [29, 31, 35, 36] to determine its reliability. The control variable was set as $Bo^{0.19}We^{-0.42}$ and the corresponding meta-analysis at an average control variable value of 0.6982 and liquid-only Reynolds number $Re_{LO} = 3117$ is shown in Figure 17. Because of its weightage (87.2% of the turbulent evaporation pressure drop data), the Rivera et al. [31] study was chosen as the control group, while the remaining studies [29, 35, 36] were the study group.

At $I^2 = 92.8$ and $Tau^2 = 16.6$ considerable heterogeneity and inconsistency were detected in the

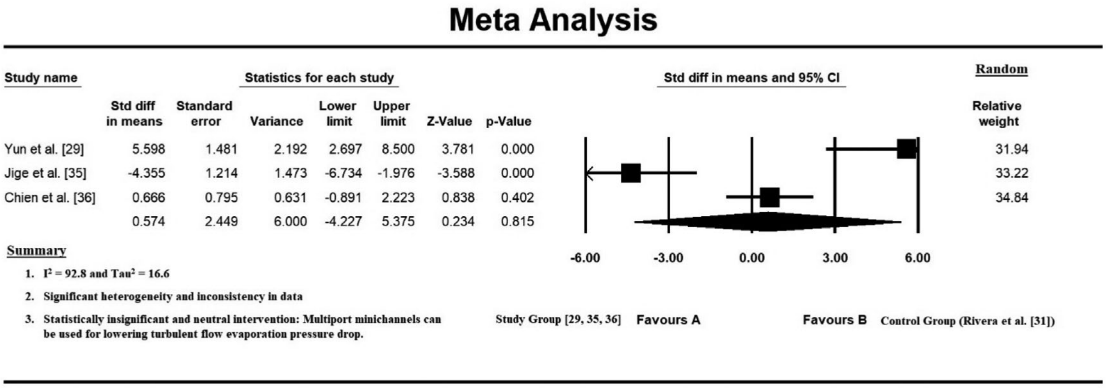
Table 6. Predictive correlations for turbulent flow evaporation pressure drop in multiport minichannels.

| Study | Deviation | | |
|---|---|---|---|
| | MBD | RMSD | Fit |
| Current study (Eq. (8))<br>$\phi_{\mathrm{LO}}^2 = 3.08Bo^{0.19}We^{-0.42}$<br>(G = 300–1320 kg/m$^2$s, q″ = 3–15 kW/m$^2$, Re$_{\mathrm{LO}}$ = 2330–5450,<br>Bo = (0.01–23) × 10$^{-7}$, We = 0.39–0.094) | 2.1% | 20.9% | 48.7% in ±10%; 82.1% in ±30%; 100% in ±50% |
| Lockhart and Martinelli [1]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\quad turb}} + \frac{1}{X_{turb,\quad turb}^2}$<br>C = 20 for Re$_{\mathrm{LO}} > 2000$ and Re$_{\mathrm{LO}} > 2000$<br>(G = 50–1500 kg/m$^2$s, T$_{\mathrm{sat}}$ = 21–29 °C, Re$_{\mathrm{LO}}$ = 1.5–124,000 and<br>Re$_{\mathrm{v}}$ = 7–86,500) | −1554% | 24,147% | 2.3% in ±50% |
| Sun and Mishima [27]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\quad turb}} + \frac{1}{X_{turb,\quad turb}^2}$<br>$C = 1.79\left(\frac{Re_{\mathrm{v}}}{Re_{LO}}\right)^{0.4}\left(\frac{1-x}{x}\right)^{0.5}$<br>(G = 50–2000 kg/m$^2$s, Re$_{\mathrm{LO}}$ = 10–37,000, Re$_{\mathrm{v}}$ = 0 to 4 × 10$^5$ and x = 0–1) | −474.5% | 2252% | 0% in ±50% |
| Kim and Mudawar [41]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\quad turb}} + \frac{1}{X_{turb,\quad turb}^2}$<br>$C = 0.39Re_L^{0.03}Su_{\mathrm{v}}^{0.1}\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{v}}}\right)^{0.35}$<br>$Su_{\mathrm{v}} = \left(\frac{\rho_{\mathrm{v}}\sigma d_{\mathrm{h}}}{\mu_{\mathrm{v}}^2}\right)$<br>(Re$_{\mathrm{LO}}$ = 3.9–89,798, G = 4–8528 kg/m$^2$s, x = 0–1, P$_{\mathrm{r}}$ = 0.0052–0.91) | −611% | 658.4% | 4.7% in ±50% |
| Choi et al. [42]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\quad turb}} + \frac{1}{X_{turb,\quad turb}^2}$<br>$C = 5.56Re_{TP}^{0.28}We_{TP}^{-0.29}$<br>$\rho_{\mathrm{TP}} = \frac{x}{\rho_{\mathrm{v}}} + \frac{1-x}{\rho_{\mathrm{L}}}$<br>$\frac{1}{\mu_{\mathrm{TP}}} = \frac{x}{\mu_{\mathrm{v}}} + \frac{1-x}{\mu_{\mathrm{L}}}$<br>$Re_{\mathrm{TP}} = \frac{Gd_{\mathrm{h}}}{\mu_{\mathrm{TP}}}$<br>and $We_{\mathrm{TP}} = \frac{G^2 d_{\mathrm{h}}}{\sigma\rho_{\mathrm{TP}}}$<br>(Re$_{\mathrm{TP}}$ = 10,000–100,000, G = 300–600 kg/m$^2$s, q″ = 10–40 kW/m$^2$, x = 0.1–0.8) | −1176% | 13,822% | 2.3% in ±50% |
| Zhang [23]<br>$\phi_{LO}^2 = 1 + \frac{C}{X_{turb,\quad turb}} + \frac{1}{X_{turb,\quad turb}^2}$<br>C = 21(1-e$^{-358/\mathrm{La}}$)<br>(G = 50–1500 kg/m$^2$s, x = 0–1, Re$_{\mathrm{LO}}$ = 90–12,204 and Re$_{\mathrm{v}}$ = 5–12,200 | −1566% | 24,533% | 2.3% in ±50% |

compiled data. As the 95% CI band of the Chien et al. [36] study crosses the null line, its data were statistically insignificant. This means that the true value of the computed two-phase multiplier $\phi_{\mathrm{LO}}^2$ was in the CI band and hence not relevant to the meta-analysis. The resultant diamond of the analysis also crossed the null line, and hence meta-analysis of the turbulent pressure drop data was statistically insignificant. The meta-analysis was inconclusive, and the current trend of deploying multiport minichannel evaporators in the turbulent regime may continue. Additional turbulent pressure drop data in the future may offer better insights into the suitability of such evaporators for turbulent flow evaporation. The cumulative meta-analysis of the data is shown in Figure 18.

## Relevance to computational modeling

Despite the recent surge in computational modeling, empirical modeling and experimental data are vital for validating such models and rendering them accurate and reliable. Computational fluid dynamics (CFD) complements experimentation by numerically visualizing a heat exchanger's flow and heat transfer mechanisms. However, CFD isn't a stand-alone technique. Any such flow visualization must be thoroughly corroborated with experimental methods such as schlieren, laser doppler anemometry, or infrared thermography. For that reason, several CFD studies [43–48] had relied on empirical data for validating and refining their computational models and the



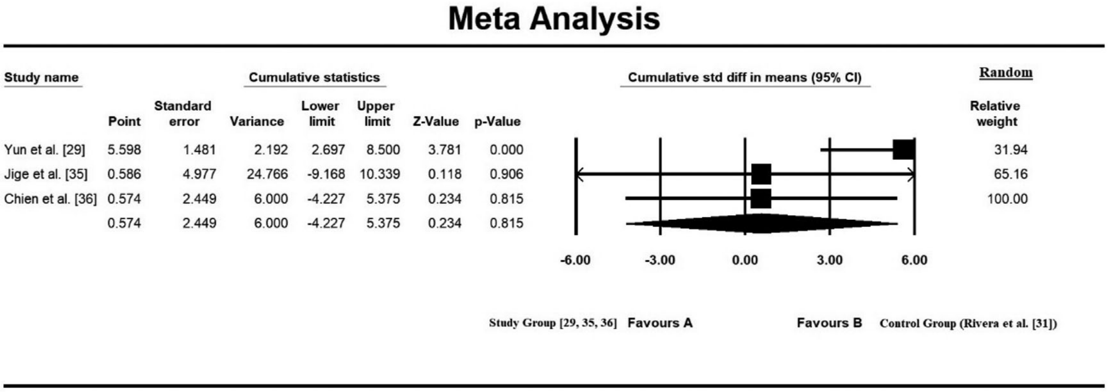
Meta Analysis

| Study name | Std diff in means | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Relative weight |
|---|---|---|---|---|---|---|---|---|
| Yun et al. [29] | 5.598 | 1.481 | 2.192 | 2.697 | 8.500 | 3.781 | 0.000 | 31.94 |
| Jige et al. [35] | -4.355 | 1.214 | 1.473 | -6.734 | -1.976 | -3.588 | 0.000 | 33.22 |
| Chien et al. [36] | 0.666 | 0.795 | 0.631 | -0.891 | 2.223 | 0.838 | 0.402 | 34.84 |
|  | 0.574 | 2.449 | 6.000 | -4.227 | 5.375 | 0.234 | 0.815 |  |

**Summary**

1. $I^2 = 92.8$ and $Tau^2 = 16.6$
2. Significant heterogeneity and inconsistency in data
3. Statistically insignificant and neutral intervention: Multiport minichannels can be used for lowering turbulent flow evaporation pressure drop.

**Figure 17.** Meta-analysis of turbulent evaporation pressure drop [29, 31, 35, 36] in multiport minichannel evaporators.



Meta Analysis

| Study name | Point | Standard error | Variance | Lower limit | Upper limit | Z-Value | p-Value | Relative weight |
|---|---|---|---|---|---|---|---|---|
| Yun et al. [29] | 5.598 | 1.481 | 2.192 | 2.697 | 8.500 | 3.781 | 0.000 | 31.94 |
| Jige et al. [35] | 0.586 | 4.977 | 24.766 | -9.168 | 10.339 | 0.118 | 0.906 | 65.16 |
| Chien et al. [36] | 0.574 | 2.449 | 6.000 | -4.227 | 5.375 | 0.234 | 0.815 | 100.00 |
|  | 0.574 | 2.449 | 6.000 | -4.227 | 5.375 | 0.234 | 0.815 |  |

**Figure 18.** Cumulative meta-analysis of turbulent pressure drop [29, 31, 35, 36] in multiport minichannel evaporators.

underlying boundary layer approximations and simplifications. It is believed that the data and correlations presented in this article will both validate and refine CFD models.

## Validation of the predictive correlations

To establish their reliability, the predictive correlations were validated with an extended database from multiport minichannels. Equations (5)–(8) are based on the number of parallel ports. Hence, only studies with multiport minichannel tubes were included in the extended database. The condensation evaluation data are listed in Table 7 [4, 5, 7–10, 26, 31, 49–53], while the evaporation evaluation data are shown in Table 8 [29, 31, 36, 54–56].

### *Condensation*

Laminar condensation friction pressure gradients were compiled from several experimental investigations in multiport minichannel condensers.

Cavallini et al. [4] reported friction pressure drop gradients for condensation of R236ea, R134a, and R410A in a 1.4 mm diameter multiport minichannel condenser. Experimental friction pressure drop measurements were conducted at a saturation temperature $T_{sat} = 40\,^{\circ}C$, mass flux $G = 200–1400\,kg/m^2s$, and vapor quality $x = 0–1$.

Park and Hrnjak [5] reported an adiabatic pressure drop during condensation of $CO_2$ in 0.89 mm diameter multiport minichannel condensers. Friction pressure gradient was measured at a saturation temperature of $T_{sat} = -15\,^{\circ}C$, mass flux $G = 200–600\,kg/m^2s$, and vapor quality $x = 0–0.9$.

Belchi et al. [7] investigated the friction pressure drop during condensation of R32 and R410A in a 1.16 mm diameter horizontal multiport minichannel condenser. The experiments were conducted at a mass flux $G = 470–800\,kg/m^2s$ and vapor quality $x = 0.1–0.9$. Widely reported correlations validated the limited data. No new correlations were proposed for the two-phase multiplier.

Belchi et al. [8] conducted condensation pressure drop experiments in a 1.16 mm diameter multiport minichannel condenser with R32 and R410A. The friction pressure drop was measured at a mass flux $G = 350–800\,kg/m^2s$, saturation temperature $T_{sat}$ =

**Table 7.** Condensation pressure gradient data for evaluation.

| Study | Fluid | No. of data<br>Laminar | <br>Turbulent | % Of data | Experimental uncertainty |
|---|---|---|---|---|---|
| Cavallini et al. [4] | R134a, R236ea, and R410A | 29 | 23 | 7.24% | 18% |
| Park and Hrnjak [5] | $CO_2$ | 39 | 11 | 6.96% | 9.7% |
| Belchi et al. [7] | R32 and R410A | 26 | 12 | 5.29% | 11.9% |
| Belchi et al. [8] | R32 and R410A | 36 | 98 | 18.66 | 11.9% |
| Jige et al. [9] | R134a, R1234Ze(E), R32, and R410A | 179 | 35 | 29.81% | Not available |
| Belchi et al. [10] | R290 | 68 | 31 | 13.79% | 11.9% |
| Rivera et al. [31] | R32 and R134a | 10 | 4 | 19.49% | ±3.3% |
| Kim and Kim [49] | R404A R455A, and R449A | 21 | 0 | 2.92% | ±0.3% to ±0.4% |
| Zhang and Webb [26] | R134a, | 2 | 0 | 0.28% | ±9% |
| Yang and Webb [50] | R12 | 1 | 5 | 0.84% | Not available |
| Ammar et al. [51] | R134a | 2 | 3 | 0.69% | ±4.2% |
| Knipper et al. [52] | R134a | 17 | 1 | 2.51% | ±1% to ±8% |
| Heo et al. [53] | $CO_2$ | 56 | 9 | 9.05% | ±1.57% |

**Table 8.** Evaporation pressure gradient data for evaluation.

| Study | Fluid | No. of data Laminar | Turbulent | % Of data | Experimental uncertainty |
|---|---|---|---|---|---|
| Yun et al. [29] | R410A | 0 | 3 | 1.62% | Not available |
| Rivera et al. [31] | R32 and R134a | 0 | 34 | 18.38% | ±3.3% |
| Chien et al. [36] | R290 | 0 | 2 | 1.08% | Not available |
| Jige et al. [54] | R32 | 34 | 0 | 18.38% | Not available |
| Eda et al. [55] | R32 | 18 | 0 | 4.32% | ±0.2% to ±6.8% |
| Kim and Kim [56] | R290, R32, R134a, R404A, R448A, and R449A | 71 | 23 | 50.81% | ±0.5% to ±0.6% |

30–40 °C, and vapor quality $x = 0.1–0.9$ and were compared with existing correlations. No new correlations for the two-phase friction multiplier were proposed.

Jige et al. [9] reported condensation pressure drop with R134a, R32, R1234Ze(E), and R410A in a 0.85 mm diameter multiport minichannel condenser. The experiments were conducted at mass flux $G = 100–500\,kg/m^2s$, saturation temperature $T_{sat} = 60\,°C$ and vapor quality $x = 0.1–0.9$. The condensation friction pressure gradient was reduced to a new friction factor correlation. The correlation based on limited data was compared successfully with existing correlations.

Belchi et al. [10] studied the condensation of propane in a 1.16 mm diameter multiport minichannel condenser. The condensation friction pressure gradient was measured at $G = 175–350\,kg/m^2s$, heat flux $q'' = 15.76–32.25\,kW/m^{2,}$ and $T_{sat} = 30\,°C$, 40 °C, and 50 °C. The data was reduced to new correlations. The limited data-based correlations were compared with widely reported correlations. No correlations were developed for the two-phase multiplier.

Rivera et al. [31] investigated the condensation of R134a and R32 in a 1.16 mm hydraulic diameter multiport minichannel condenser. The experiments conducted at a mass flux of $G = 350–700\,kg/m^2s$, saturation temperature $T_{sat} = 40\,°C$, and vapor qualities $x = 0.1–0.8$ indicated that the condensation friction pressure gradient decreased with saturation pressure.

Kim and Kim [49] studied the condensation of R404A, R455A, and R449A in a 0.8 mm diameter multiport minichannel condenser. The friction pressure gradient was measured at a mass flux of $G = 310–620\,kg/m^2s$, saturation temperature $T_{sat} = 45\,°C$, and vapor quality $x = 0.3–0.8$. The pressure gradient decreased with vapor density.

Zhang and Webb [26] measured the frictional pressure gradient for condensation of R134a in a 2.13 mm diameter multiport minichannel condenser. The two-phase multiplier was deduced from the measurements at a mass flux of $G = 400–600\,kg/m^2s$, vapor quality $x = 0.2–0.9$, and saturation temperature $T_{sat} = 40–65\,°C$ were fit satisfactorily by a new predictive correlation.

Yang and Webb [50] investigated the condensation of R12 in a 2.64 mm diameter multiport minichannel condenser. The condensation friction pressure gradient was measured at a mass flux $G = 400–1400\,kg/m^2s$, saturation temperature $T_{sat} = 65\,°C$, and vapor quality $x = 0.1–0.9$.

Ammar et al. [51] studied the condensation of R134a in a 0.69 mm, and a 0.718 mm diameter multiport minichannel automotive condensers. The condensation pressure drop gradient was measured at mass flux $G = 490–1600\,kg/m^2s$, vapor quality $x = 0.2–0.8$ at a saturation temperature $T_{sat} = 61\,°C$.

Knipper et al. [52] measured the friction pressure drop during the condensation of R134a with and without lubricants in a 0.53 mm and a 0.91 mm diameter multiport minichannel condenser. The experiments were conducted at saturation pressures of $P_{sat} = 15–20\,bar$, mass flux $G = 400–800\,kg/m^2s$, and vapor quality $x = 0.2–0.8$.

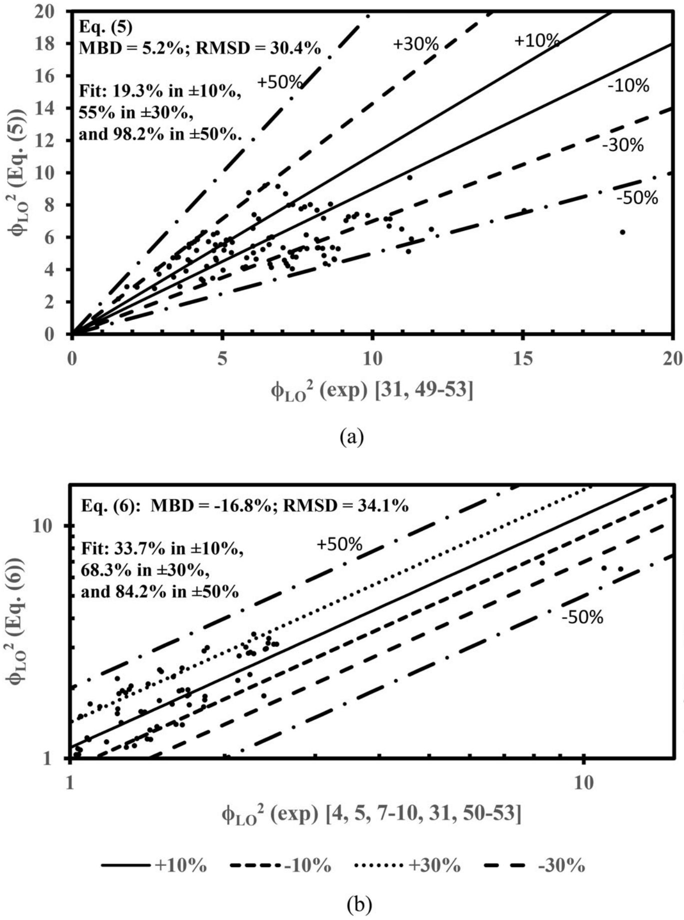


**Figure 19.** Validation of the condensation two-phase multiplier correlations: (a) Laminar condensation; (b) Turbulent condensation.

Heo et al. [53] investigated the condensation of $CO_2$ in three multiport minichannel condensers with hydraulic diameters $d_h = 0.68–1.5$ mm at saturation temperatures $T_{sat} = -5$ to 0 °C. The corresponding mass flux G ranged from 400 kg/m$^2$s to 600 kg/m$^2$s, while the vapor quality varied between 0.1 to 1.0.

The laminar condensation equation Eq. (5) was evaluated with selected data [26, 31, 49–53] for laminar flow. As shown in Figure 19a, Eq. (5) fit 19.3% of the evaluation data within ±10%, 55% in ±30%, and 98.2% in ±50%. The low MBD of 5.2% and RMSD of 30.4% confirm the accuracy and reliability of Eq. (5)

The turbulent condensation equation Eq. (6) was also validated with data [4, 5, 7–10, 31, 50–53] and is shown in Figure 19b. At an MBD of −16.8% and RMSD of 34.1%, Eq. (6) fit 33.7% of the evaluation data within ±10%, 68.3% within ±30%, and 84.2% within ±50%.

These excellent fits confirm the accuracy and reliability of Eqs. (5) and (6).

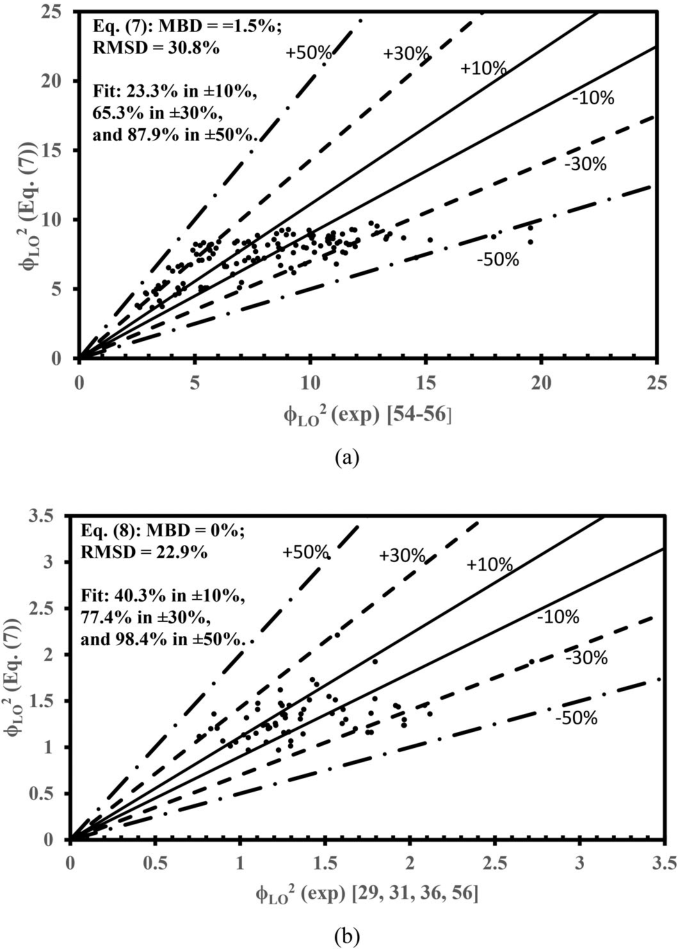


**Figure 20.** Validation of turbulent two-phase multiplier correlations: (a) Laminar evaporation (b) Turbulent evaporation.

## Evaporation

Evaporation pressure drop data were also collected from multiport minichannel evaporators for validating the predictive correlations.

Yun et al. [29] reported an experimental friction pressure drop for the evaporation of R410A in two multiport minichannel evaporators with diameters of 1.36 mm and 1.44 mm, respectively. The R410A friction pressure gradient was measured at a saturation temperature $T_{sat} = 5–10$ °C, mass flux $G = 200–400$ kg/m$^2$s, and vapor quality $x = 0.2–0.8$.

Rivera et al. [31] investigated the evaporation of R134a and R32 in a 0.715 mm multiport minichannel evaporator at a saturation temperature $T_{sat} = 5–12.5$ °C and mass flux $G = 500–1300$ kg/m$^2$s.

Chien et al. [36] reported the evaporation friction pressure drop for R-717 and R-290 in a 0.83 mm multiport minichannel evaporator. Experiments were conducted at mass flux $G = 500$ kg/m$^2$s and saturation temperature $T_{sat} = 6$ °C.

Jige et al. [54] measured the friction pressure drop gradient during the condensation of R32 with and without lubricants in a 0.82 mm multiport minichannel evaporator. The mass flux G varied from 200 kg/m$^2$s to 400 kg/m$^2$s, while the saturation temperature was $T_{sat} = 15\,°C$ and vapor quality $x = 0.1–0.9$.

Eda et al. [55] investigated evaporation in a 0.81 mm multiport minichannel evaporator. The friction pressure gradient was measured at a constant heat flux $q'' = 22.5\,kW/m,^2$ mass flux $G = 200–400\,kg/m^2s$, saturation temperature $T_{sat} = 15\,°C$ and vapor quality $x = 0.1–0.9$.

Kim and Kim [56] reported the evaporation pressure drop in a 1.61 mm multiport minichannel evaporator. The experiments were conducted at a saturation temperature of $T_{sat} = 15\,°C$, heat flux $q'' = 2.8–6.5\,kW/m,^2$ mass flux $G = 200–400\,kg/m^2s$, and vapor quality $x = 0.1–0.9$.

As shown in Figure 20a, Eq. (7) fit 23.3% of the extended laminar evaporation pressure drop data [54–56] within ±10%, 65.3% in ±30%, and 87.9% in ±50%. The corresponding low values of MBD and RMSD at −1.5% and 30.8% confirm the accuracy and reliability of Eq. (7).

The evaluation of the turbulent evaporation correlation is shown in Figure 20b. At an MBD of 0% and RMSD of 22.9%, Eq. (8) fit 40.3% of the extended data [29, 31, 36, 56] within ±10%, 77.4% within ±30% and 98.4% in ±50%. This validates the reliability of Eq. (8).

## Conclusions

This article compiled over two thousand phase-change pressure drop data from twenty-nine sources and developed predictive correlations for the two-phase multiplier. Some of the significant findings of this study are as follows:

1. Current two-phase multiplier predictive correlations based on limited data were generally poor fits to the compiled data. Widely reported correlations based on past data were also poor predictors of the two-phase multiplier. None of them were reliable benchmark standards.
2. For laminar condensing flows in multiport minichannel condensers, only the reduced pressure-based Zhang and Webb [26] correlation fit the compiled pressure drop data reasonably well. Their correlation included 55.3% of the data within ±50%, while Eq. (5) fit 67.3% of the data within ±50%. However, at an MBD and RSMD of −100.6% and 330.5%, the Zhang and Webb [26] correlation was much worse than Eq. (5) at an MBD of 18.8% and RMSD of 46.6%. None of the other widely reported correlations fit either the laminar or turbulent condensation pressure drop data well.
3. Compared to other widely reported correlations, the Zhang and Webb [26] correlation marginally better fit the laminar evaporation pressure drop data. Their correlation fit 28.4% of the data within ±50% and was comparable to the 57.3% data fit by Eq. (7) within ±50%. However, at an MBD of −1163.1% and RMSD of 4690.3%, the quality of the Zhang and Webb [26] correlation was much worse than that of Eq. (7) at an MBD of 14% and RMSD of 49.8%. None of the other widely reported correlations yielded an excellent fit to laminar and turbulent evaporation pressure drop data.
4. Meta-analysis proved to be a valuable analytical tool and revealed that multiport minichannels were particularly suitable for lowering pressure drop during turbulent condensation and laminar evaporation. Therefore, it is recommended that multiport mincihannel condensers be deployed in the turbulent flow regime while multiport minichannel evaporators should be deployed in the laminar flow regime. Meta-analysis was inconclusive in other cases.

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