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Research article

Numerical assessment of ceramic micro heat exchangers working with nanofluids by Taguchi optimization approach

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ABSTRACT

The rapid advancements in microsystems technology have necessitated the exploration of innovative materials for efficient thermal management in micro heat exchangers. This research delves into the performance evaluation of three advanced ceramics: ZrB_2, BeO, and Si_3N_4 as alternative micro heat exchanger fabrication materials. The study systematically assessed the ceramics' interaction with Al_2O_3-nanofluids across diverse volume percentages and mass flow rates using the Taguchi optimization method. Beryllium oxide emerged as the superior material, registering warm outlet temperatures as low as 64.86 °C and cold outlet peaks at 31.68 °C. Sensitivity analyses further underscored the critical role of inlet temperature on outlet dynamics, with warm and cold outlets showing significances of ~72% and ~99%, respectively. Additionally, the research pinpointed 0.75 vol% as the optimal Al_2O_3-nanofluid content, yielding the most favorable performance metrics across the ceramics.

KEYWORDS

Micro heat exchanger
Taguchi method
Optimization
Advanced ceramics
Numerical method

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1. Introduction

Heat exchangers are essential tools in thermal management. These devices transfer heat between two or more separate fluids, ensuring they do not mix. Their wide use in many areas, such as the car industry, HVAC systems, and power generation, shows their crucial role. One main reason for using heat exchangers is to increase energy efficiency and make operations smoother [1–4]. In the design of heat exchangers, a vital principle is to expand the surface area that touches the fluids. By focusing on this design idea, heat exchangers can ensure that heat transfer is effective and reaches high levels of efficiency. Over the years, the area of heat exchanger design has seen the creation of many different styles to fit specific needs. Some of these styles are the shell and tube, plate, and finned tube designs. Each of these heat exchanger types has its own set of benefits. However, they also come with challenges that need to be solved to work the best. This shows that while the primary goal remains the same, the ways to reach it can vary based on the specific design of the heat exchanger [5, 6].

The recent technological advancements, especially in the electronics sector, have accentuated the need for compact and efficient thermal management solutions. Micro heat exchangers have been developed specifically to address this requirement. Despite their small size, these devices can dissipate significant amounts of heat, making them ideal for modern electronic devices. This allows for the miniaturization of electronic devices without compromising performance [6, 7].

Ultra-high temperature ceramics (UHTCs) are known for handling sweltering conditions, making them vital in today's advanced materials work. Zirconium diboride (ZrB_2) is special since it can take heat up to 3245 °C, which is excellent for high-tech applications, especially in rockets and planes [8–11]. Beryllium oxide (BeO) performs well in hot situations and is favored in various industries because of its unique properties [12–14]. Silicon nitride (Si_3N_4) is another standout, strong, and reliable in hot conditions, making it a top choice for advanced plane and space technology. In machinery that manages and transfers heat, like heat exchangers, advanced ceramics offer improved functions, helping these devices work better and last longer, even in

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sweltering conditions. As industries continue to innovate and face heat challenges, the role and importance of advanced ceramics in research and practical applications will surely grow [15, 16].

Another notable advancement in heat transfer technology is the study and application of nanofluids. These are created by mixing tiny particles, often derived from metals or metal oxides, into standard liquids like water or oil. Introducing these nanoparticles increases the inherent heat transfer abilities of the liquid. Moreover, by adjusting the kind or amount of the added nanoparticles, one can influence the fluid behavior of the liquid. This means changing characteristics such as flow consistency and pressure behavior. This versatility gives nanofluids the possibility for numerous uses, from improving electronic cooling to enhancing the performance of air conditioning systems. Merging nanofluids with micro heat exchangers might define the future direction of thermal management approaches. This combination offers improved operational effectiveness, higher durability, and economic efficiency [17, 18].

In 1981, Tuckerman et al. [19] set the stage for advancements in the thermal management of electronic circuits by introducing silicon-made microchannel heat exchangers in high-performance liquid cooling for integrated surface circuits, achieving a surface temperature of roughly 71 °C. Building on this, Fedorov et al. [20] unveiled a 3D model for a microchannel heat sink to comprehend dual-fluid flow and heat transfer in electronics, discovering complex thermal flow patterns in silicon and suggesting means to enhance microchannel cooling efficiency. Meanwhile, Fend et al. [21] empirically studied High-Temperature Ceramic Micro Heat Exchangers (HTHE) with silicon carbide blades, revealing a notable efficiency of up to 65% at sweltering temperatures of 1000 °C using air for heat transfer.

On a parallel trajectory, Kee et al. [22] delved into ceramic microchannel heat exchangers operating on a counter-flow principle, underscoring ceramics' capability to endure much higher temperatures than metals. With inlet temperatures nearing 750 °C, their experiments reported efficiencies touching 70%, making them apt for high-temperature and rigorous chemical settings. Conversely, Alm et al. [23] investigated an aluminum oxide (Al_2O_3)-made micro heat exchanger, documenting a thermal efficiency spanning from 0.1 to 0.22 based on a mass flow rate from 20 to 120 kg/h.

The applicability of ceramic-made microchannel heat exchangers in microturbines was probed by Carman et al. [24], emphasizing the requisite for a high-efficiency recuperator with minimal pressure drop to obtain the highest cycle efficiency. Their research spotlighted Silicon Carbon Nitride (SiCN) ceramics as the prime choice for these exchangers due to their resilience in explosive gas environments, even at temperatures up to 1300 °C. In a quest for optimal design, Nagarajan et al. [25] harnessed computational fluid dynamics software FLUENT to devise configurations for blades in High-Temperature Ceramic Plate-Fin Heat Exchangers (PFHE). Their work canvassed an array of blade designs and fluids, concluding the saw-tooth blade design at a mere 0.05 mm thickness to yield the finest heat transfer output.

Nekahi et al. [26] accentuated ceramics' durability as the materials of choice for heat exchangers. Using numerical simulations, they extrapolated the superior heat transfer attributes of a microchannel exchanger crafted from TiB_2–SiC. Dwivedi et al. [27] embarked on the development of a ceramic microchannel heat sink tailored for corrosive atmospheres and elevated temperatures. Leveraging the finite element method, they deduced pronounced enhancements in heat transfer using ZrB_2 composites fortified with SiC and CNT. In a pioneering attempt, Shi et al. [28] merged genetic algorithms with modeling to revolutionize the performance of ceramic microchannel heat exchangers. Their novel approach, targeting the exchanger's inlet, resulted in substantially harmonized flow and a marginal rise in pressure drop. Further, Huo et al. [29] employed Al_2O_3–water nanofluids in heat exchangers, recording a pronounced upswing in the heat transfer coefficient and overall efficiency. Finally, in a similar vein, Nguyen et al. [30] investigated a miniature heating device leveraging Al_2O_3–water nanofluid, marking a 40% surge in the convective heat transfer coefficient.

We comprehensively assess and optimize micro heat exchangers constructed from advanced ceramics, specifically, ZrB_2, BeO, and Si_3N_4 in the present study. These ceramics are tested with Al_2O_3-nanofluids at different volume percentages and mass flow rates. The core objective is to decipher the nuanced influences of different material properties and fluid flow parameters on the performance metrics of heat exchangers. Three critical fluid flow parameters are zeroed in on mass flow rate, nanofluids volume percentage, and materials. The performance optimization is gauged using four pivotal output metrics: cold outlet temperature, warm outlet temperature, effectiveness, and heat transfer. These metrics are subjected to rigorous analysis using ANOVA calculations to derive insights that can potentially propel the efficacy of ceramic-made micro heat exchangers working in tandem with nanofluids to new heights.

2. Methodology

2.1. Design of research

To optimizing processes, the Taguchi technique employs orthogonal arrays as a convenient method for experiment design. This technique was designed to not just expedite the process, but also to enhance and enrich the statistical information derived from a small set of outcomes. Such a viewpoint helps to identify the role and importance of parameters influencing the process and reveals any imaginable correlation between output and input values. Employing the Taguchi methodology helps to clarify the optimal parameters for designing and manufacturing a product with the aim to improve performance, quality, or standard [31–36].

The technique classifies the quality characteristics into three categories: "nominal is better", "smaller is better", or "bigger is better" [37]. This study aims to evaluate the performance of micro heat exchangers made of ZrB_2, BeO, and Si_3N_4 ceramics that work with nanofluids. Four output parameters (temperature of cold outlet, temperature of warm outlet, effectiveness, and heat transfer) are assessed. The quality characteristics of the mentioned parameters are analyzed according to Table 1.

Table 1. Studied output parameters and relevant quality characteristics.

Output parameter	Quality characteristic
Temperature of warm outlet	Smaller is better
Temperature of cold outlet	Bigger is better
Heat transfer	Bigger is better
Effectiveness	Bigger is better

Table 2. Selected levels for studied parameters.

Parameters	Level 1	Level 2	Level 3
Mass flow rate (kg/h)	15	50	85
Ceramic material	ZrB_2	BeO	Si_3N_4
Nano Al_2O_3 additive (vol%)	0.5	0.75	1

Qualitek-4 software is used for statistical studies and experiment design. The importance and contribution of the mass flow rate, the type of ceramic material, and the amount of nano Al_2O_3 additive on the performance of micro heat exchangers are investigated. The chosen levels for these input parameters are listed in Table 2. In designing an experiment with three parameters at three levels, 27 runs are needed in the normal full factorial way. However, using the Taguchi method, the number of runs is reduced to 9. The used L9 orthogonal array is presented in Table 3. After compiling the results, analysis of variance (ANOVA) is employed to estimate the importance and contribution of all input parameters on the performance of output ones.

2.2. Geometry of the micro heat exchanger

This paper investigates a symmetrical micro heat exchanger chosen as a reference model. This specialized micro heat exchanger is meticulously engineered to work with water-based nanofluids as both cold and warm fluids. Its plates are fabricated from three advanced ceramics: ZrB_2, Si_3N_4, and BeO. These plates incorporate microchannels to optimize heat transfer. Detailed dimensions of these plates and microchannels are demonstrated in Table 4. The study specifically focuses on a symmetrical section of these channels to analyze heat transfer dynamics, aligning with the heat exchanger's inherent symmetry. A visual representation of the symmetrical micro heat exchanger is provided in Fig. 1.

2.3. Governing equations and numerical method

The heat transfer process in a heat exchanger involves two mechanisms: conduction in the ceramic-made plates and convection in the fluids. To model this process, three domains are considered: two for the cold and hot water flows, and one for the solid plates. The equations governing the behavior of the fluid regions include those for mass conservation, fluid dynamics (Navier-Stokes), and thermal energy [38]:

$$\rho\nabla.(u) = 0 \tag{1}$$

$$\rho(\frac{\partial u}{\partial t} + u.\nabla u) = -\nabla p + \nabla.\left(\mu(\nabla u + (\nabla u)^T - \frac{2}{3}\mu(\nabla u)I\right) \tag{2}$$

$$\rho c_p u.\nabla T + \nabla.q = Q \tag{3}$$

where ρ, μ, u, T, c_p, and q denote density (kg/m^3), fluid viscosity (Pa.s), velocity (m/s), temperature (K), heat capacity (J/kg.K), and heat flux (w/m^2), respectively. In this study, heat production (Q) within the fluid is not considered. The heat transfer rate, denoted as q, is calculated based on Fourier's principle of thermal conduction [7]:

$$q = -k\nabla T \tag{4}$$

where k (w/m.K) is the coefficient of the heat transfer of the material.
For the solid domain, the governing equation is the 3D steady-state heat conduction formula as follows [26]:

$$\nabla.q = Q \tag{5}$$

Conjugate heat transfer is employed to establish the connection between the previously mentioned equations pertaining to the fluid and solid domains. These equations are systematically solved employing the COMSOL Multiphysics software, yielding velocity and temperature distributions within both the solid and fluid domains.
To tackle the governing equations effectively, a mesh is applied to both the solid and fluid domains, as illustrated in Fig. 2. The convergence and outcome accuracy can be influenced by the number of mesh elements. Consequently, a mesh independence assessment is conducted, determining that a minimum of 30,500 elements is required to ensure reliable results.
A crucial metric for assessing the performance of the heat exchanger is its effectiveness, symbolized as ε. This is determined by comparing the actual heat transferred to the theoretical maximum heat that could be transferred within the heat exchanger. This calculation is made using the outlet and inlet temperatures of the fluids involved [39]:

$$\varepsilon = \frac{T_{wo} - T_{wi}}{T_{ci} - T_{wi}} \tag{6}$$

where w and c subscripts indicate the warm and cold fluids, respectively, while i and o represent inlet and outlet, respectively.

Table 3. The L9 orthogonal array as the numerical analysis procedure.

Run No.	Mass flow rate (kg/h)	Ceramic material	Nano Al_2O_3 additive (vol%)
1	15	ZrB_2	0.5
2	15	BeO	0.75
3	15	Si_3N_4	1
4	50	ZrB_2	0.75
5	50	BeO	1
6	50	Si_3N_4	0.5
7	85	ZrB_2	1
8	85	BeO	0.5
9	85	Si_3N_4	0.75

Table 4. The plate micro heat exchanger's geometric data.

	Warm fluid	Cold fluid
Number of plates	3	3
Number of passages	17	17
Total number of channels	51	51
Channel length (cm)	1.25	1.25
Channel width (mm)	0.250	0.250
Channel height (mm)	0.320	0.420
Wall thickness (mm)	0.520	0.520
Layer thickness (mm)	0.990	0.880

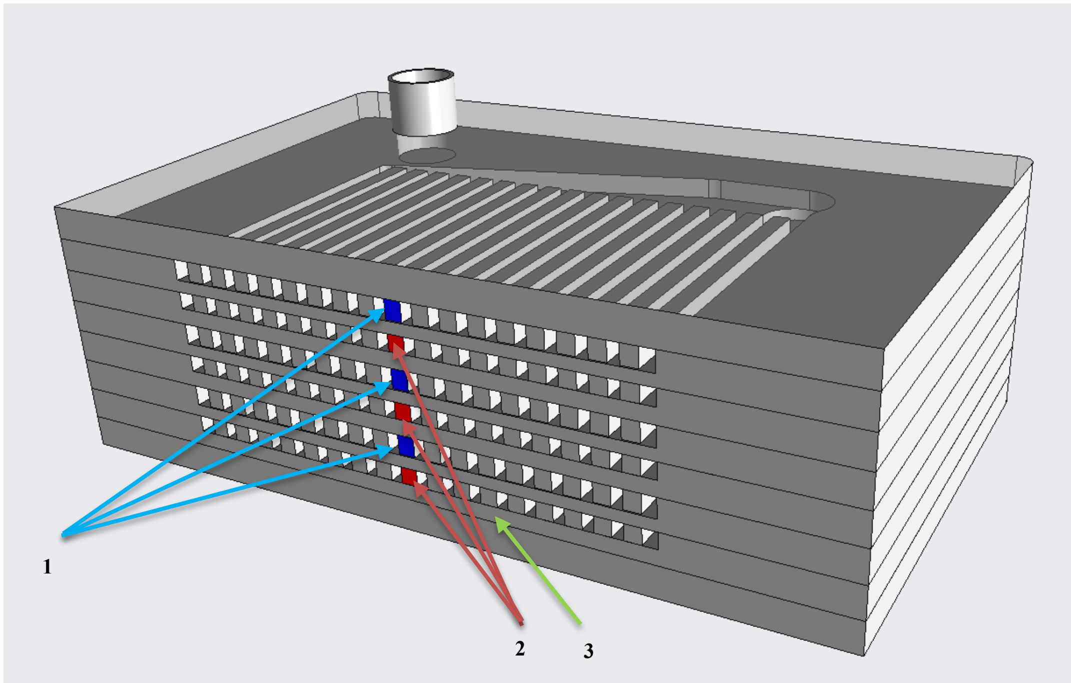

Fig. 1. Schematic of the micro heat exchanger's layout: 1) Channels for cold flow, 2) Channels for warm flow, and 3) The solid ceramic body connecting them.

Heat transfer in nanofluids, especially thermal conduction, is a complex phenomenon due to the interactions between the base fluid and nanoparticles. The effective thermal conductivity (k_{eff}) of nanofluids is one of the most important parameters for understanding the mechanism of thermal conduction.

The effective thermal conductivity of nanofluids can be influenced by several factors, including the volume fraction of nanoparticles in the fluid, the shape and size of nanoparticles, the thermal conductivity of both the base fluid and nanoparticles, and the interactions at the particle-fluid interface [40, 41]. These factors play a critical role in determining the heat transfer characteristics of nanofluids.

Hence, an empirical model based on recent research focusing on

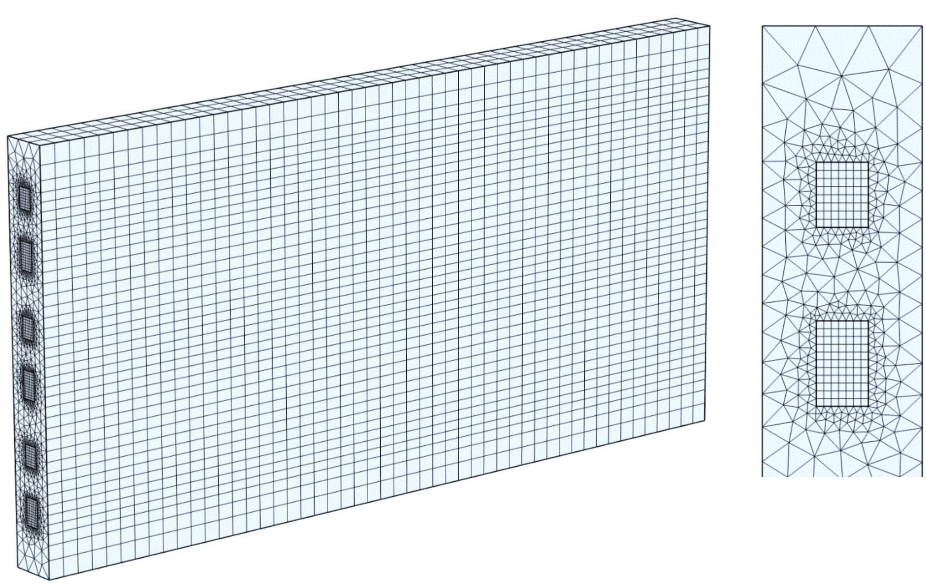

Fig. 2. Meshed computational domain.

particle sizes ranging from 5 to 100 nanometers has been proposed by the Singaporean team led by Murshed and colleagues [42]. In the current study, equation (7), recommended by Murshed et al. [42] has also been employed to calculate k_{eff}.

$$k_{eff}=\frac{k_{bf}\left[1+0.27\phi^{4/3}\left(\frac{k_p}{k_{bf}}-1\right)\right]\left[1+\frac{0.52\phi}{1-\phi^{1/3}}\left(\frac{k_p}{k_{bf}}-1\right)\right]}{1+\phi^{4/3}\left(\frac{k_p}{k_{bf}}-1\right)\left(\frac{0.52\phi}{1-\phi^{1/3}}+0.27\phi^{1/3}+0.27\right)} \quad (7)$$

where k_{eff}, k_{bf}, k_p, and ϕ, respectively, represent the effective thermal conductivity of nanofluids, the thermal conductivity of the base fluid, the thermal conductivity of nanoparticles, and the volume fraction of nanoparticles.

3. Results and discussion

Using COMSOL Multiphysics, the heat transfer analysis of the micro heat exchanger constructed with advanced ceramics is conducted, yielding temperature distributions in both the solid and fluid domains. These results serve as a basis for optimizing the crucial parameters that impact the heat exchanger's performance. Initially, the numerical outcomes are compared to the findings presented by Alm et al. [23] to validate their accuracy. Fig. 3 illustrates the disparity between the numerical results from this study and the reference data, affirming the reliability of the employed numerical methodology.

After being sure about the accuracy of the applied numerical method, the proposed heat exchanger for different runs, outlined in Table 3, is investigated. Fig. 4 displays the temperature distribution across the entire micro heat exchanger constructed with suggested advanced ceramics, presenting contour plots for all nine cases. These temperature distributions serve as input parameters for the optimizing algorithm. Subsequently, the outcomes for various output parameters, including cold outlet temperature, warm outlet temperature, effectiveness, and heat transfer, are documented in Table 5. Furthermore, this table includes the grand averages of the outcomes along with their corresponding standard deviations.

As indicated in Table 1, the primary goal is to minimize the warm outlet temperature while maximizing the effectiveness, heat transfer,

Table 5. Output parameters computed through numerical analyses.

Run No.	Warm outlet temp. (°C)	Cold outlet temp. (°C)	Heat transfer (J/s)	Effectiveness (%)
1	68.29	28.96	495	27.14
2	64.86	31.68	575	31.43
3	67.66	29.45	528	27.93
4	74.73	23.60	830	19.09
5	71.86	25.89	986	23.41
6	74.77	23.47	806	19.65
7	76.53	22.23	1091	16.84
8	73.66	24.60	1258	21.08
9	76.51	22.18	1070	17.41
Grand average	72.10	25.78	849	22.66
Standard deviation	4.22	3.45	274	5.14

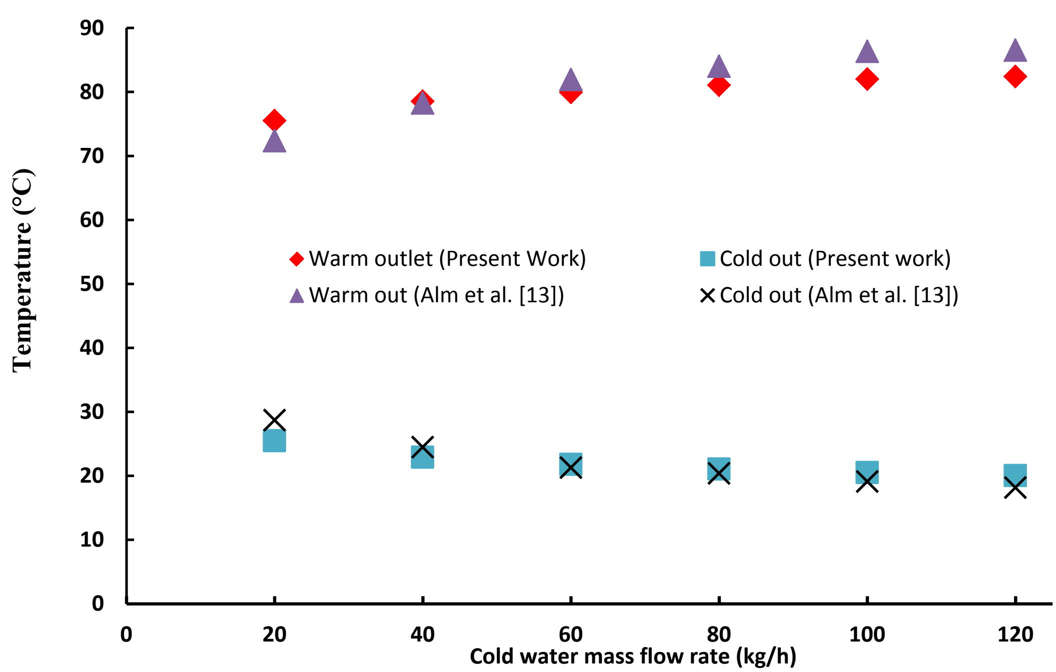

Fig. 3. The comparison of the water outlet temperature to the data presented by Alm et al. [23].

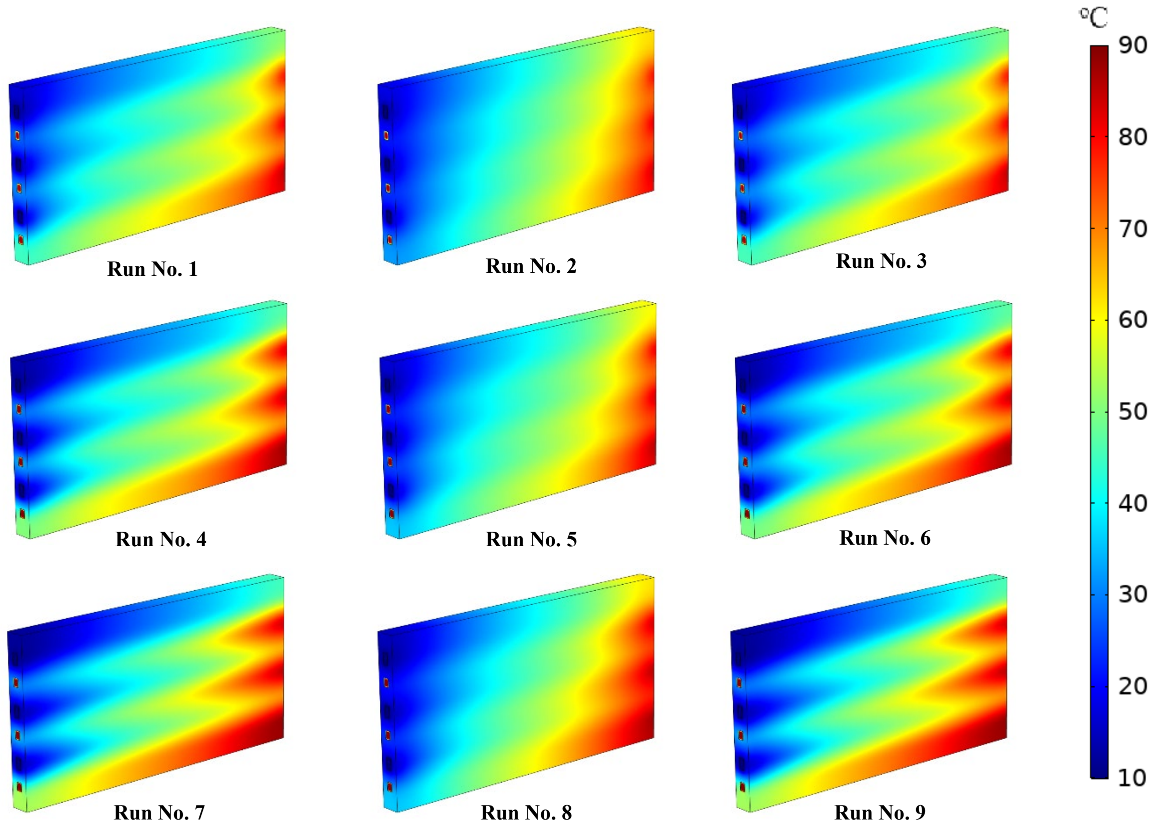

Fig. 4. Temperature contours for a micro heat exchanger constructed using suggested ceramic materials in various scenarios.

and cold outlet temperature. Consequently, among the nine test runs, Run No. 2 demonstrates the best performance in terms of effectiveness and warm outlet temperature. Additionally, it attains the highest temperature for the outgoing cold fluid. However, due to its lower flow rate, it exhibits an overall moderate thermal performance. Conversely, Run No. 8 achieves the highest heat transfer among the tested runs. According to Fig. 4, Runs featuring the BeO material display a uniform temperature distribution, whereas runs involving the other two proposed materials exhibit less favorable distributions, particularly at higher flow rates.

3.1. Temperature of warm outlet

Fig. 5 presents the average values of the main effect plots for the temperature of the warm outlet. With rising the mass flow rate from 15 kg/h to 50 kg/h, the mean value of the temperature of the warm outlet rises exceedingly from ~66.9 °C to ~73.8 °C. With more enhancement in the mass flow rate to 85 kg/h, the mean value is again enhanced to ~75.6 °C, but the intensity of this increase is less compared to the previous state. This enhancement in war outlet temperature is due to Re increment and consequent higher heat convection. The average values for the temperature of the warm outlet in the micro heat exchangers made of ZrB_2, BeO, and Si_3N_4 are ~73.2 °C, ~70.1 °C, and ~73.0 °C, respectively. Therefore, it seems that from the viewpoint of warm outlet temperature, the diboride and the nitride ceramics have almost the same performance, which is slightly different from the oxide ceramic. Also, apparently, the amount of nano alumina additive does not have much effect on the temperature of the warm outlet, as the average temperature goes from ~72.2 °C to ~72.0 °C with the increase of the additive amount from 0.5 vol% to 0.75 vol% and then to 1 vol%. The ANOVA data of the significance of studied parameters (mass flow rate, type of ceramic material, and

Table 6. ANOVA data of studied parameters on the temperature of warm outlet.

Parameter	Degrees of freedom	Sum of squares	Variance	F-ratio	Pure sum	Significance (%)
Mass flow rate	2	124.566	62.283	1767.989	124.496	87.514
Ceramic material	2	17.528	8.764	248.780	17.457	12.271
Nano Al_2O_3 additive	2	0.091	0.045	1.302	0.021	0.014
Other/error	2	0.070	0.035	-	-	0.201
Total	8	142.257	-	-	-	100.000

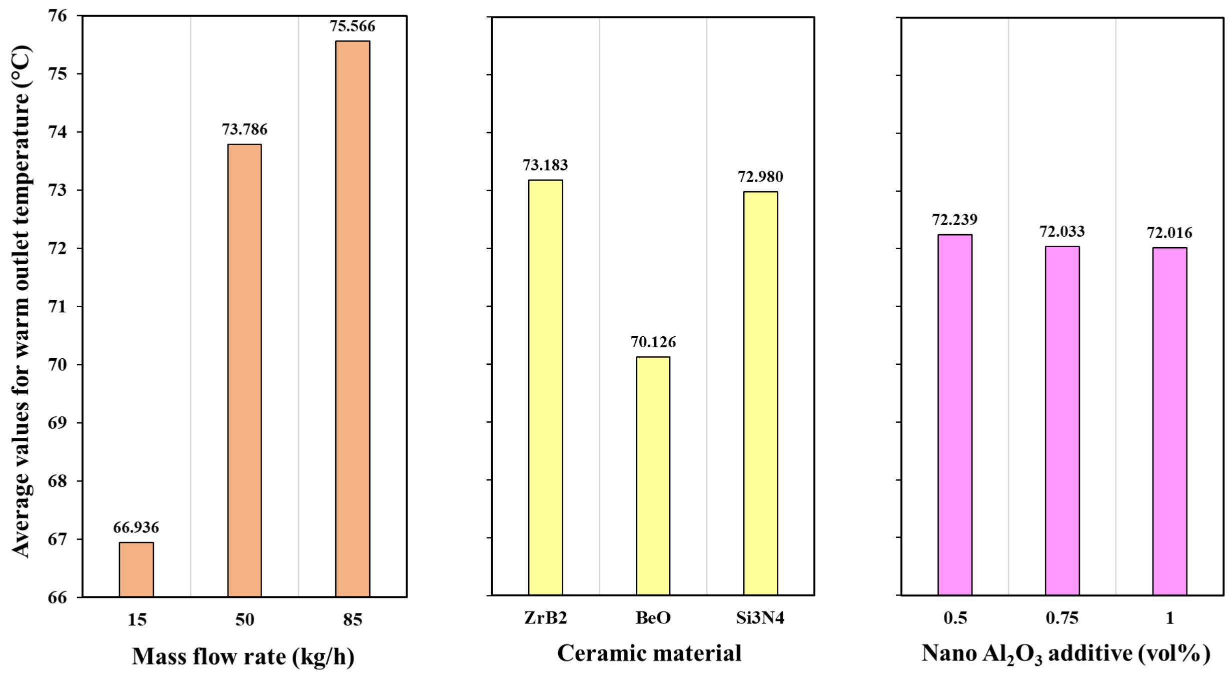

Fig. 5. Average values main effect plots for the temperature of warm outlet.

amount of nano Al_2O_3 additive) on the temperature of the warm outlet is reported in Table 6. Based on such statistical data, the mass flow rate with a significance of ~88% is identified as the main controlling parameter on the temperature of the warm outlet due to its direct effect on empowering the convection phenomena. The type of ceramic material has an importance of ~12%, but according to ANOVA, the amount of nano Al_2O_3 additive is completely insignificant. This insignificance of the Al_2O_3 additive is due to the high convective heat transfer of water and the small heat transfer resistance of the convection phenomena in comparison with conduction heat transfer resistance. The significance of error and/or another unstudied parameter is about 0%, which can be ignored.

The significance pie chart of the studied parameters on the temperature of the warm outlet is shown in Fig. 6. As can be seen from this

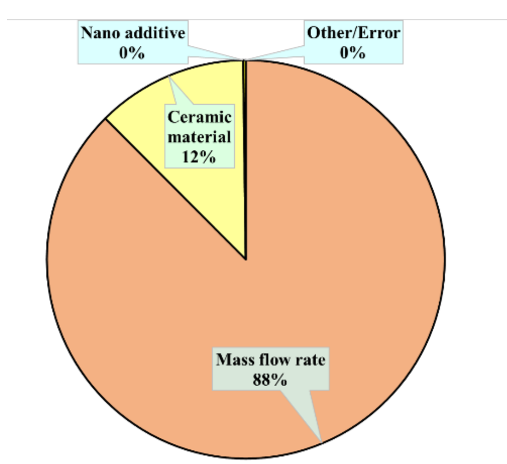

Fig. 6. Significance pie chart of studied parameters on the temperature of warm outlet.

graphical chart, the mass flow rate is very important. At the same time, the amount of nano additive has no place in statistical comparison. Therefore, based on the studied parameters and selected levels in the methodology of this research, the mass flow rate has a remarkable momentousness on the temperature of the warm outlet.

Table 7 presents the contributions and the optimal states of all studied parameters on the temperature of the warm outlet. The lowest temperature of the warm outlet is desirable and achievable at the optimal states of the mass flow rate of 15 kg/h (level 1), the BeO as the ceramic material (level 2), and the nano additive content of 1 vol% (level 3). The contribution values of mass flow rate, type of ceramic material, and amount of nano Al_2O_3 additive are computed to be -5.16 °C, -1.97 °C, and -0.08 °C, respectively. Thus, the whole contribution values from all studied parameters are -7.21 °C. As provided in Table 5, the grand mean of the temperature of the warm outlet is 72.10 °C which may be dropped by considering the optimum levels. Assuming the total contributions of -7.21 °C, the temperature of the warm outlet is decreased to 64.89 °C.

Table 7. Contribution of studied parameters on the temperature of warm outlet.

Parameter	Level	Level description	Contribution (°C)
Mass flow rate	1	15 kg/h	-5.16
Ceramic material	2	BeO	-1.97
Nano Al_2O_3 additive	3	1 vol%	-0.08
Total contributions			-7.21
Grand average			72.10
Expected outcome at optimal state			64.89

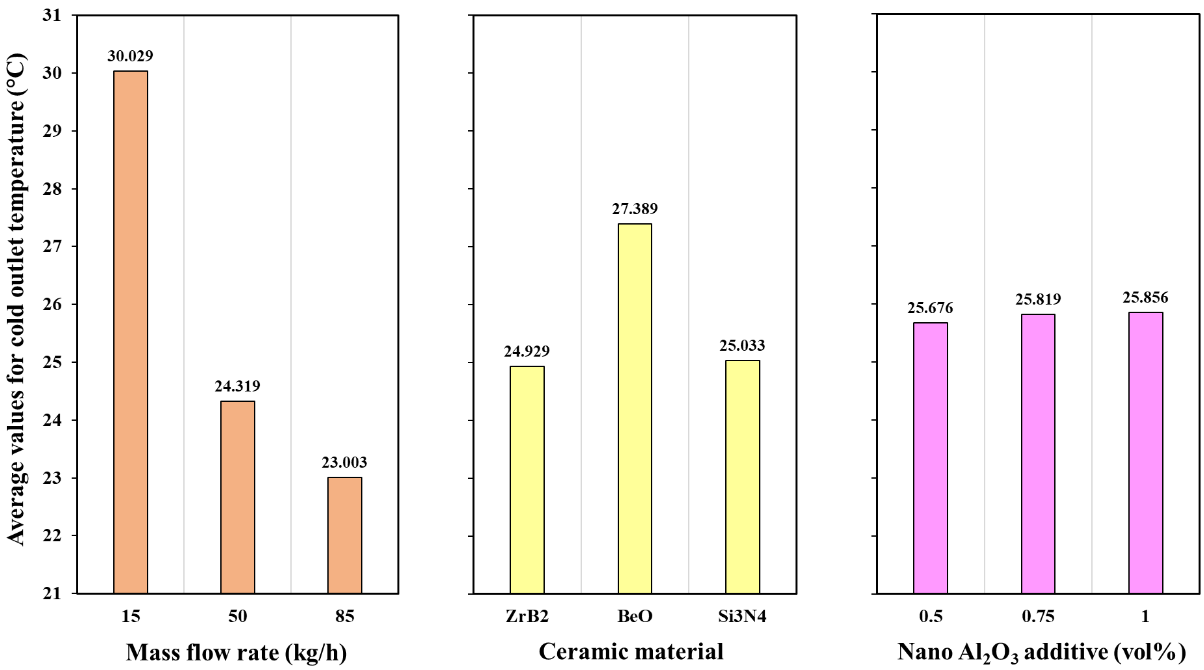

Fig. 7. Average values main effect plots for the temperature of cold outlet.

3.2. Temperature of cold outlet

Fig. 7 shows the average values of the main effect plots for the temperature of the cold outlet. With enhancing the mass flow rate from 15 kg/h to 50 kg/h, the mean value of the cold outlet temperature decreases from ~30.0 °C to ~24.3 °C, but with extra enhancement in the mass flow rate to 85 kg/h, the mean value insignificantly lessens to ~23.0 °C. By changing the ceramic material from ZrB_2 to BeO, the mean value of the temperature of the cold outlet increases from ~24.9 °C to ~27.4 °C, but it decreases to ~25.0 °C if Si_3N_4 is selected as the material for micro heat exchanger manufacturing. In other words, diboride and nitride materials still show the same performance. This can be attributed to the thermal conductivity of the ceramic material. BeO has higher thermal conductivity compared to nitride and diboride. If 0.5 vol%, 0.75 vol%, and 1 vol% nano alumina additives are added to the fluid, the average temperature of the cold outlet reaches ~25.7 °C, ~25.8 °C, and ~25.9 °C, respectively. Therefore, from the viewpoint of the temperature of the cold outlet, the amount of nano additives in the fluid does not have a special effect on the performance of the system.

Table 8 provides the ANOVA data of the significance of studied parameters (mass flow rate, type of ceramic material, and amount of nano Al_2O_3 additive) on the temperature of the cold outlet. In accordance with this statistical assessment, the mass flow rate is determined as the major influential parameter that controls the temperature of the cold outlet with a significance of ~88%. Meanwhile, the significance of the type of ceramic material is ~12%. However, the amount of nano Al_2O_3 additive is not important and the significance of the other/error is also around 0%. It is interesting to note that the statistical significance of all input parameters in both output parameters (warm and cold outlet temperatures) is almost the same. Fig. 8 illustrates the significance pie chart of the studied parameters on the temperature of the cold outlet. Similar to the pie chart related to the temperature of the warm outlet, it is clearly seen that the mass flow rate with a significance of ~88% is the major influential parameter. The type of ceramic material is also 12% significant. The importance of nano additives and other unknown parameters or errors is very small and close to zero.

Table 8. ANOVA data of studied parameters on the temperature of cold outlet.

Parameter	Degrees of freedom	Sum of squares	Variance	F-ratio	Pure sum	Significance (%)
Mass flow rate	2	83.711	41.855	1286.825	83.646	87.637
Ceramic material	2	11.615	5.807	178.559	11.550	12.101
Nano Al_2O_3 additive	2	0.054	0.027	0.883	0.000	0.000
Other/error	2	0.064	0.032	-	-	0.262
Total	8	95.446	-	-	-	100.000

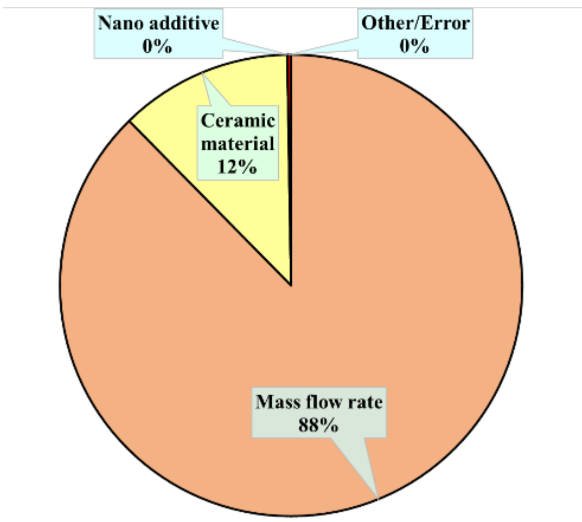

Fig. 8. Significance pie chart of studied parameters on the temperature of cold outlet.

The optimum state and the contributions of all studied parameters on the temperature of the cold outlet are listed in Table 9. The highest temperature for the cold outlet, which is desired, can be achieved with a mass flow rate of 15 kg/h (level 1), using BeO as the ceramic material (level 2), and adding 1 vol% nano alumina to the fluid (level 3). The contribution values of mass flow rate, type of ceramic material, and nano additive content are calculated to be 4.25 °C, 1.61 °C, and

Table 9. Contribution of studied parameters on the temperature of cold outlet.

Parameter	Level	Level description	Contribution (°C)
Mass flow rate	1	15 kg/h	4.25
Ceramic material	2	BeO	1.61
Nano Al_2O_3 additive	3	1 vol%	0.07
Total contributions			5.93
Grand average			25.78
Expected outcome at optimal state			31.71

0.07 °C, respectively. Hence, the whole contribution values from all studied parameters are 5.93 °C. As provided in Table 5, the grand mean of the temperature of the cold outlet is 25.78 °C, which can be promoted by selecting the optimum levels of all parameters. Thus, the temperature of the cold outlet is anticipated to rise to 31.71 °C if the contributions of all input parameters are considered.

3.3. Heat transfer

The heat transferability of a heat exchanger is one of the crucial factors influencing its performance. The average values of the main effect plots for heat transfer are illustrated in Fig. 9. The mean value of heat transfer remarkably rises from ~533 J/s to 874 J/s with enhancing the mass flow rate from 15 to 50 kg/h. If the mass flow rate is elevated to 85 kg/h, the mean value increases again to ~1340 J/s. If ZrB_2 or Si_3N_4 is used in the fabrication of the micro heat exchanger, the average value

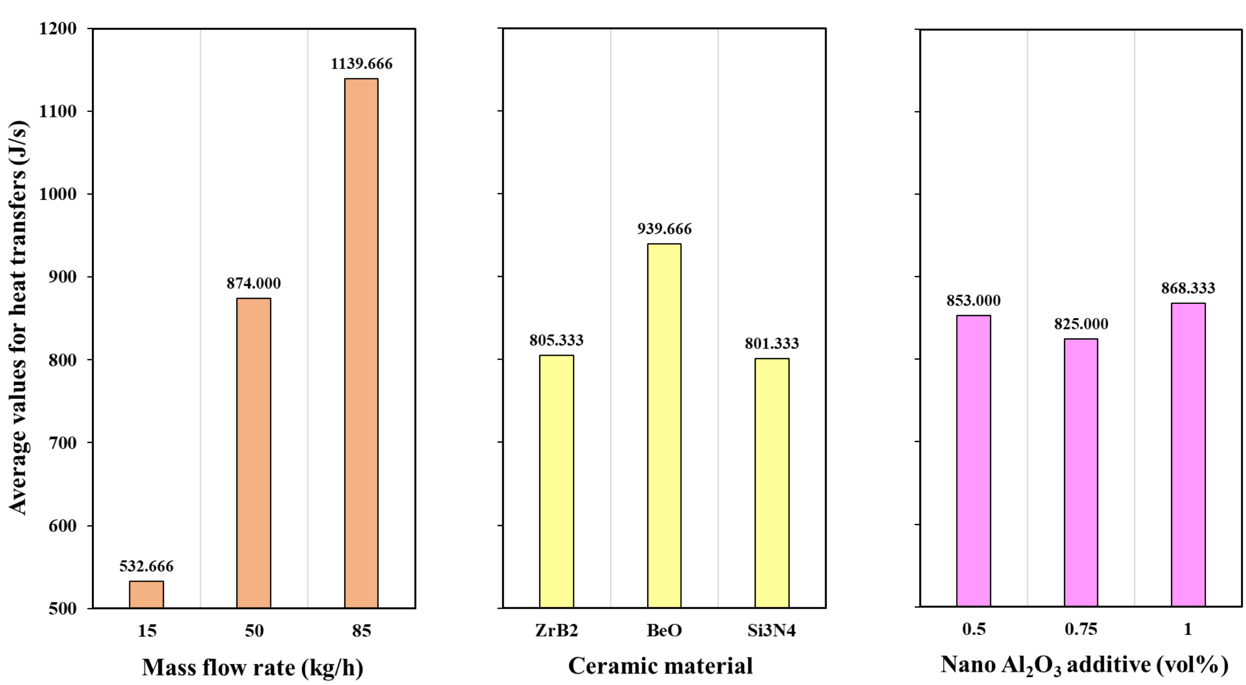

Fig. 9. Average values main effect plots for heat transfer.

Table 10. ANOVA data of studied parameters on heat transfer.

Parameter	Degrees of freedom	Sum of squares	Variance	F-ratio	Pure sum	Significance (%)
Mass flow rate	2	555536.009	277768.004	160.221	552068.719	92.150
Ceramic material	2	37197.474	18598.737	10.728	33730.184	5.630
Nano Al_2O_3 additive	2	2896.782	1448.391	0.835	0	0.000
Other/error	2	3467.288	1733.644	-	-	2.220
Total	8	599097.555	-	-	-	100.000

of heat transfer reaches ~805 J/s or ~801 J/s, respectively. Therefore, similar to what was observed in the review of the previous output parameters, diboride and nitride materials have the same performance from the point of view of heat transfer. Anyway, if BeO is used in the manufacturing process, the mean value of heat transfer increases and reaches ~940 J/s. Therefore, it seems that oxide ceramics have better thermal conductivity than other ceramic materials. About the amount of nano Al_2O_3 additive, if its value is increased from 0.5 vol% to 0.75 vol%, the mean value of heat transfer decreases from 853 J/s to 825 J/s, but with a further increase of nano additive to 1 vol%, the mean value of heat transfer enhances again and reaches ~868 J/s. However, the increasing or decreasing trend of this parameter seems unimportant.

The ANOVA data of the significance of the studied parameters (mass flow rate, type of ceramic material, and amount of nano Al_2O_3 additive) on the heat transfer are summarized in Table 10. As expected, the mass flow rate is again found as the key controlling parameter on the heat transfer, but this time with more significance around 92%. According

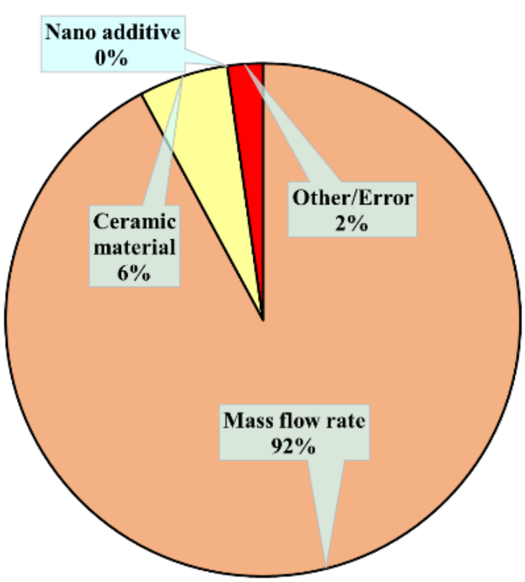

Fig. 10. Significance pie chart of studied parameters on heat transfer.

to the statistical results, the significance of the type of ceramic material is less than 6%. Therefore, from a mathematical viewpoint, the importance of the type of ceramic material on heat transfer is reduced to about half compared to its effect on the temperatures of warm and cold outlets. The ANOVA considers the significance of nano additive content on the heat transfer of micro heat exchangers to be absolute zero. The interesting point is that the errors and/or parameters that have not been investigated have a significance of ~2%.

Fig. 10 displays the significance pie chart of studied parameters on heat transfer that clearly illustrates the major role of mass flow rate. Although the amount of nano Al_2O_3 additive is insignificant, the type of ceramic material has a minor significance of ~6%. In other words, to achieve the maximum efficiency of the system from the approach of heat transfer, only the control of the mass flow rate is sufficient, and other factors do not play a significant role in this regard.

The optimal state and the contributions of all studied parameters on heat transfer are presented in Table 11. The highest heat transfer is obtainable at these states: selecting a mass flow rate of 85 kg/h (level 3), choosing BeO as the ceramic material for micro heat exchanger construction (level 2), and adding 1 vol% nano Al_2O_3 additive (level 3). The contribution values of mass flow rate, type of ceramic material, and nano additive content on the heat transfer are computed as 291 J/s, 91 J/s, and 19 J/s, respectively. Hence, whole contribution values from all studied parameters are 401 J/s. The grand mean of heat transfer is 849 J/s, as also reported in Table 5. Therefore, by taking the contributions of all parameters at the optimal state into consideration, the heat transfer can be boosted to reach 1250 J/s.

Table 11. Contribution of studied parameters on heat transfer.

Parameter	Level	Level description	Contribution (J/s)
Mass flow rate	3	85 kg/h	291
Ceramic material	2	BeO	91
Nano Al_2O_3 additive	3	1 vol%	19
Total contributions			401
Grand average			849
Expected outcome at optimal state			1250

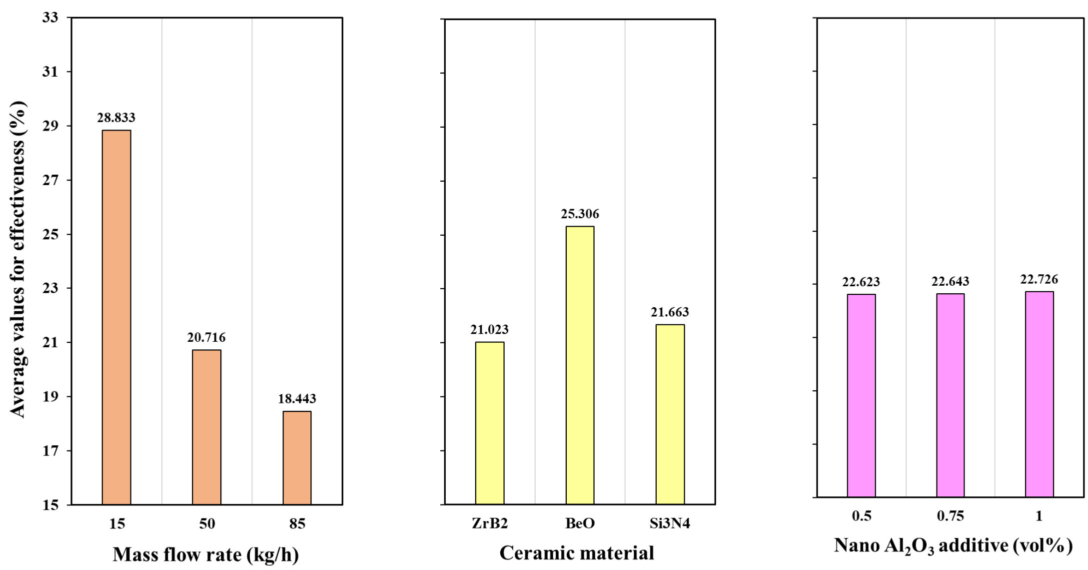

Fig. 11. Average values main effect plots for effectiveness.

3.4. Effectiveness

The average values of the main effect plots for effectiveness are illustrated in Fig. 11. The mean value of this parameter sharply decreases from ~28.8% to ~20.7%, with a rise in the mass flow rate from 15 to 50 kg/h. The mean value drops with a lower decreasing trend to ~18.4% if the mass flow rate is elevated to 85 kg/h. The mean value for effectiveness increases from ~21.0 to ~25.3% by changing the ceramic material from ZrB_2 to BeO but decreases to ~21.7% if Si_3N_4 is selected as the micro heat exchanger material. Here, it appears that oxide ceramic shows better performance than other nitride and diboride ceramics. By adding nano Al_2O_3 additives in the amounts of 0.5 vol%, 0.75 vol%, and 1 vol%, the average effectiveness values of ~22.6%, ~22.6%, and ~22.7% are obtained, respectively. Thus, it can be easily claimed that within the range of changes in the amount of nano additives examined in this research, no significant difference in the effectiveness is seen. In general, in order to improve the performance of the micro heat exchanger, it is desired to have a higher effectiveness. Therefore, it is recommended to make it from BeO ceramic and consider a mass flow rate of 15 kg/h. Although the nano additive in the amount of 1 vol% has a slightly better result than the others, however, since the amount of this difference is not so significant, it is logically and economically better to choose the minimum additive content, which is 0.5 vol%.

Table 12 lists the ANOVA data of the significance of the studied parameters (type of ceramic material, mass flow rate, and amount of nano Al_2O_3 additive) on the effectiveness. The mass flow rate is detected as the general parameter with an importance of ~85%. Statistically, the significance of the type of the chosen ceramic material is about 15%. The significance of errors/unstudied parameters as well as the amount of nano Al_2O_3 additive is almost 0%.

The significance pie chart of the studied parameters on the effectiveness of micro heat exchangers is shown in Fig. 12. This chart graphically displays that the mass flow rate and the type of ceramic material are ranked 1 and 2, respectively, in terms of effectiveness. The nano additive percentage and unexamined parameters or errors are statistically insignificant.

The contributions and optimum states of all studied parameters on the effectiveness of micro heat exchangers are summarized in Table 13. According to these calculations, the best effectiveness is approachable at a mass flow rate of 15 kg/h (level 1) using BeO as the ceramic material for making the micro heat exchanger (level 2) with 1 vol% nano Al_2O_3 as the fluid additive (level 3). Of course, since the amount of nano additive, as mentioned before, does not have much effect, it is better to choose 0.5 vol% nano Al_2O_3 from the economic point of view. The contributions of mass flow rate, type of ceramic material, and nano additive content on the effectiveness are estimated as 6.17%, 2.64%, and 0.06%, respectively. Therefore, whole contributions from all studied parameters are 8.87%. As mentioned in Table 5, the grand mean of effectiveness is 22.66%, so this output parameter can be boosted to 31.53% by choosing the optimal levels for the studied parameters.

Table 12. ANOVA data of studied parameters on effectiveness.

Parameter	Degrees of freedom	Sum of squares	Variance	F-ratio	Pure sum	Significance (%)
Mass flow rate	2	179.000	89.500	32940.516	178.995	84.809
Ceramic material	2	32.030	16.015	5894.398	32.025	15.173
Nano Al_2O_3 additive	2	0.018	0.009	3.380	0.012	0.006
Other/error	2	0.004	0.002	-	-	0.012
Total	8	211.054	-	-	-	100.000

Table 13. Contribution of studied parameters on effectiveness.

Parameter	Level	Level description	Contribution (%)
Mass flow rate	1	15 kg/h	6.17
Ceramic material	2	BeO	2.64
Nano Al_2O_3 additive	3	1 vol%	0.06
Total contributions			8.87
Grand average			22.66
Expected outcome at optimal state			31.53

4. Conclusions

In the presented research, a meticulous evaluation of micro heat exchangers constructed from advanced ceramics was undertaken. The performance of three prominent advanced ceramics, ZrB_2, BeO, and Si_3N_4, was assessed in the context of their interaction with Al_2O_3-nanofluids. The Taguchi optimization method served as the backbone for this evaluation, offering a systematic and user-friendly approach. The salient findings from this research are encapsulated as follows:

- Warm outlet temperature: Beryllium oxide (BeO) consistently showcased superior performance, achieving warm outlet temperatures as low as 64.86 °C.
- Cold outlet temperature: BeO also excelled in cold outlet temperatures, registering values as high as 31.68 °C, emphasizing its standout thermal management capabilities.
- Heat transfer dynamics: BeO's thermal management capabilities were further highlighted by its ability to achieve efficient heat transfer rates, making it a prime candidate for high-end thermal applications.
- Nanofluid concentration: An optimal concentration of 0.75 vol% for Al_2O_3-nanofluids was identified, yielding the best performance metrics across all advanced ceramics tested.
- Material influence: Among the advanced ceramics, BeO emerged as the most influential in determining the overall performance of the heat exchanger, showcasing its potential as a leading material for advanced thermal management solutions.
- Outlet temperature sensitivity: The research underscored the profound influence of the inlet temperature with a significance of ~72% on the temperature of the warm outlet. Additionally, the temperature of the cold outlet was found to be highly sensitive to the inlet temperature, with the inlet temperature being the dominant item, showcasing a significance of ~99%.
- Effectiveness in heat exchangers: Elevated effectiveness is paramount for the optimal performance of heat exchangers. The research highlighted the pivotal role of the mass flow rate in determining this effectiveness, with a significance of ~100%.

Finally, this research offers valuable insights into the potential of advanced ceramics, especially BeO, in micro heat exchanger fabrication, setting the stage for future advancements in thermal management solutions.

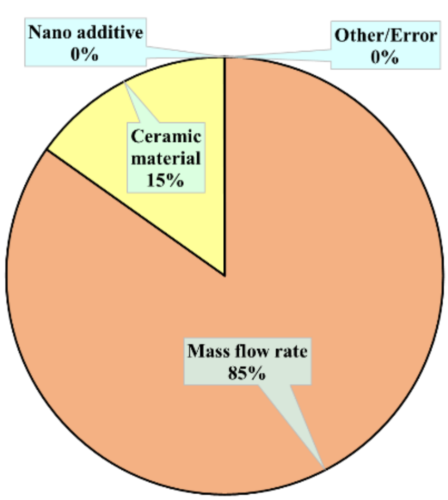

Fig. 12. Significance pie chart of studied parameters on effectiveness.

CRediT authorship contribution statement

Mohsen Naderi: Software, Data curation, Visualization, Writing – original draft.
Mohammad Vajdi: Conceptualization, Project administration, Supervision, Writing – review & editing.
Farhad Sadegh Moghanlou: Conceptualization, Supervision, Methodology, Writing – review & editing.
Hossein Nami: Software, Validation, Methodology.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The authors declare no competing interests.

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