



A review of convective heat transfer in cavity-channel assemblies

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Keywords

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Abstract

Convective heat transfer induced in open cavities is one of the main pillars that the topic of energy saving relies on. This article reviews and categorizes the results of researches on mixed convection in open cavity connected with a channel and highlights the gap that should be filled in future works. It is found that the best heat and mass transfer is attained when the source of heat and/or species is located at a vertical wall of the cavity where it opposes the flow direction. The review has revealed that the experimental studies are relatively scarce where it 10% of the total reviewed studies, while those dealing with nanofluids and porous media are 9% for each. It is found that the process of injection or aspiration of the flow have received very few studies despite its promised improvement of the heat and mass transfer. Furthermore, few researches have studied the contamination removing from the cavity.

1. Introduction

Convective heat transfer induced in open cavities is one of the main pillars that the topic of energy saving relies on. This importance stems from its wide range of technical processes such as heat exchange for cooling and heating fluid as in nuclear reactors [1], materials removing from cavities [2], controlling of fire in buildings [3], thermal management of electronic components and solar energy [4], heat exchangers [5] and food industry. The mixed convection is recalled when the natural convection is insufficient to transfer heat. Several mechanisms induce the mixed convection like driving one or

more walls in contact with the fluid [6], rotating cylinder(s) immersed within the fluid [7,8] or forcing the fluid itself through a heated boundary. Mixed convection heat transfer in a channel with open cavities is reviewed in this article. Better understanding of such a phenomenon will assist in suitable thermal design and improving the heat transfer rate. Observations and conclusions of lots of numerical articles, which have been published in the last decades contribute in a better understanding of the phenomenon. On the other hand, experimental setups are more efficient and pertinent

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[9]. Nevertheless, several aspects remain unclear and continue to be the object of active research throughout the world.

The impacts of geometrical and physical parameters on the convective exchanges in the cavity-channel are presented. Among the most important ones, the aspect ratio, the inclination, the nature of the coolant fluid, the thermal boundary conditions and the characteristics of the fluid and of the enclosure boundaries.

2. Numerical solution and/or experimental technique approaches

Mixed convective phenomena are treated numerically and/or experimentally. The experimental approaches give trusted and stable results and not limited in a specified range such as compressible, laminar or Newtonian fluids. The numerical approach requires the solution of non-linear partial differential equation systems consistent with fluid mechanics and thermodynamics conservation principles. The numerical solution of the problem depends on the characteristics of the resulting flow. In each case, an appropriate complex method must be used to obtain a reliable solution. The continuously improving numerical methods and computer technology facilitate deeper analysis of certain aspects of mixed convection such as Artificial Neural Network (ANN) [10] and Lattice-Boltzmann Method (LBM) [11].

3. Mixed convection in the cavity–channel assembly

Several investigations considered the mixed convection in clear, porous or multilayer cavities connected with a channel in different cases such as filling with fluids or nanofluids. The shape of the cavity may be square, rectangular, triangular, trapezoidal and wavy. The thermal and/or solutal boundary conditions also accounts the case of the mixed convection, for example if the active wall of the cavity is prescribed opposing to the flow direction in the cavity, then the case is called opposing and, contrary, the case is called assisting as shown in Figure 1. Depending on the shape of the cavity, several configurations will be treated in the present review and will be devoted to two categories, depended on the shape of the cavity, regular and complex.

3.1. Mixed convection in the clear cavity–channel assembly

The convective exchanges in confined domains strongly depend on the cavity geometry. Accordingly, several configurations have been treated. Manca et al. [1] in 2003 studied numerically the effect of the heated wall location on the mixed convection of air in a channel with a U-shaped open cavity. One of the cavity walls was heated by a uniform heat flux, while the other walls were thermally insulated. Three different heating modes were considered (assisting, opposing, and heating from below). The effects of Richardson number (Ri), Reynolds number (Re) and the ratio of the width of the inflow and outflow ports to the heat source length (H/D) were investigated. They concluded that, when Re and Ri numbers increase, the maximum temperature decreases. Also, it was found that the opposing forced flow

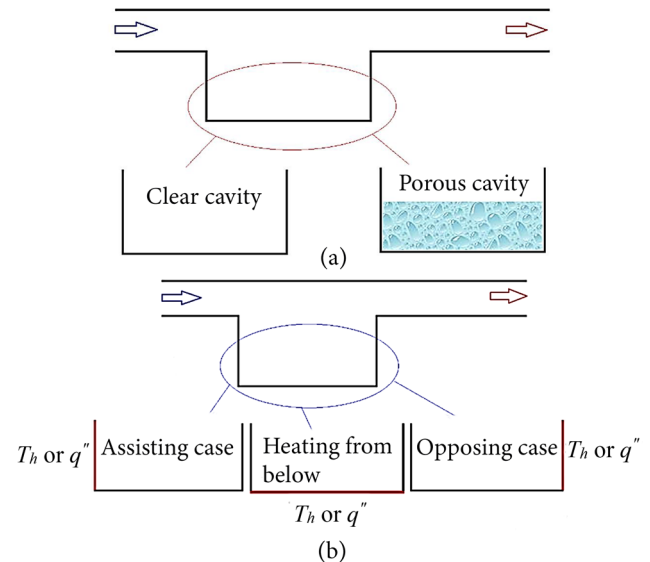


Figure 1. Various cases of cavity-connecting channel: (a) Clear and porous cavities. (b) Cases depending on the boundary condition.

had the best thermal performance. Fang [2] focused his study on the effect of mixed convection on transient hydrodynamic removal of contaminants from a rectangular cavity located below a horizontal channel. The cavity was subjected to a constant heat flux at its bottom wall. The results showed that the change in Gr had a significant effect on the flow field orientation and cleaning efficiency. Leong et al. [3] performed computation of the combined convection in a channel with a cavity heated from below. Air was pumped into the channel at a uniform velocity and temperature. They concluded that the flow field was controlled by Re and Gr and the AR had a significant effect on the flow field orientation. Andreozzi et al. [4] adjusted the left sidewall of the cavity at uniform heat flux, while the top adiabatic wall of the channel was considered moving at a constant velocity in two different directions. They suggested correlations of Nusselt number in terms of Ri and Re . Carozza et al. [5], 2005, explored the mixed convection in open cavity which was located under a channel. It was found that the Nu presents maximum values at the ratio between the channel and cavity height $H/D = 0.1$. Brown and Lai [12] inspected the double diffusive mixed convection of air in a horizontal channel with an underneath open cavity. The bottom wall of the cavity was maintained at high temperature and concentration. Fresh air was pumped into the channel at a uniform velocity and a cold temperature and concentration. They suggested correlations for the natural, forced and the mixed convection based on the scale analysis. Buonomo et al. [13] analyzed the steady combined convection of air in an open cavity filled with a fluid-saturated porous medium. Two different geometrical configurations were considered namely (horizontal channel with a cavity at the lower wall (U-shaped cavity) and a vertical channel with a cavity at its right sidewall (C-shaped cavity). The wall of the cavity on the inflow side was heated at uniform heat flux. They concluded that the two considered configurations exhibited similar

behaviors for low values of Ri and Re numbers. Also, in all cases, the maximum wall temperature value for U-shaped cavity was lower than that noted in C-shaped one. Aminossadati and Ghasemi [14] addressed an interesting numerical data regarding the mixed convection of air entered the horizontal channel integrated with an open rectangular cavity. The cavity was subjected to a discrete heat source at three different locations (left, right and bottom walls). It was found that, the heat transfer was enhanced with increasing the Aspect Ratio (AR) of the cavity. The mixed convection assisting air flow in 3D horizontal channel-square cavity assembly was considered numerically by Stiriba [15]. Both the left and right-side walls of the cavity were kept at an isothermal hot and cold temperatures, respectively. It was found that Nu increases with increasing Ri for all considered ranges of Re .

Wong and Saeid [16] considered the opposed mixed convection from a jet impingement cooling in an open cavity inside the channel filled with a porous medium. They deduced that Nu augments with the increase in Rayleigh number (Ra). Rahman et al. [17] explored the mixed convection in a horizontal channel with an open rectangular cavity numerically. A heated hollow cylinder was located inside the cavity. It was found that the Nu at the heated surface enhances as Ra and thermal conductivity ratio K increased and it was irrespective to Pr . Rahman et al. [18] performed a numerical computation of the combined laminar and steady forced and natural convection in 2D channel with an open triangular heated cavity. The magnetic field and Joule heating effects were investigated also. It was found that the heat transfer increases by increasing Re and Pr . Contrarily, it was decreased by increasing Ha and J . Selimefendigil and Yurddas [19] considered the impact of the pulsating flow on the mixed convection of air inside a horizontal channel with a square cavity heated from below and a left vertical side. Their main conclusions were that the heat transfer enhancement is increased with Str for all considered values of Re and $Ri = 100$. Selimefendigil. [20] described numerically the two-dimensional laminar mixed convection of air in a square cavity, which is linked to a horizontal channel. It was found that, at $Re = 800$, the Nu at $Ri = 10$ is smaller compared with that found at $Ri = 5$. Mehrez et al. [21] considered the entropy production along with the convective heat transfer of the nanofluids flowing in a horizontal channel with an open cavity. Heat transfer and entropy generation analysis were investigated for various types of nanoparticles (Cu, Al_2O_3 , CuO and TiO_2). They concluded that the heat transfer and the entropy generation increase with the increase of Re , Ri , ϕ and varied with AR and nanoparticle types. Also, it was deduced that the maximum enhancement of heat transfer is found for Cu-water nanofluid. Stiriba et al. [22] discussed the 3D laminar mixed convection of air in an open cavity located underneath a channel. It was found that, at low values of Ri and Re the flow becomes steady, while the increase in Re and Ri brings

the flow to be transient. Rahman et al. [23] presented computations of conjugate mixed convection in a channel with a thick-walled cavity. They concluded that the heat transfer is an increasing function of K ratio. Also, the Nu was increased with increasing of Ri except at $D = 0.5$ where it was decreased with increasing of D . Sidik and Jahanshaloo [24] performed a study on the possibility of removing contaminants from a cavity located under a horizontal channel. They concluded that, the increase of Gr rises the rate of contaminant removal at the considered value of Reynolds number ($Re = 50$). A numerical study of the entropy generation in the assisting mixed convection of Cu-water nanofluid in an inclined open cavity connected to a horizontal channel was presented by Mehrez et al. [25]. The results showed for various value of Re , Ri , ϕ and the inclination angle γ . They deduced that, the entropy generation is affected by the inclination angle γ and this depends on Re and ϕ . Sharma et al. [26] solved the mixed convection in a channel grooved by a cavity with a baffle downward towards the core of the cavity. They solved the problem using an in-house Computational Fluid Dynamics (CFD) code depending on the Finite Volume Method (FVM) with SIMPLE algorithm. The position of the hot wall was altered according to get opposing and assisting mixed convection. The positive role of the baffle was one of the main conclusions. Timuralp and Altaç [27] examined the fluid flow and heat transfer in a 3D cavity located at the bottom of a horizontal square duct. The effects of the AR of the cavity, duct height to cavity height ratio, Ri and Re were studied and discussed. They concluded that, the Nu increased by increasing the heights ratio between duct and cavity. Similar numerical investigation to Refs. [19] and [20] was carried out by Selimefendigil [28]. He used the same geometry and the boundary condition of both the channel and cavity. The distinct aspect was that the mixed convection was pulsating flow for varies range of Ri at $Re = 50$. It was found that the heat transfer enhances with an increase in the velocity amplitude. Burgos et al. [29] studied transient steady laminar mixed convection of air in a square cavity located at the bottom of a channel. The results computed by LBM and compared with ANSYS-FLUENT for validation. They deduced that at $Ri \geq 1$, a clear enhancement in the heat transfer rate was noticed. Also, it was found that the flow is unsteady for $Re \geq 500$ and $Ri = 10$, whereas the buoyancy force becomes negligible with $Ri \leq 0.1$ at any value of Re . A numerical study of the generation of entropy was presented by Zamzari et al. [30] where the mixed convection in an open cavity connected to a horizontal channel was inspected. It was found that the heat transfer decreases by the increase of the cavity aspect ratio. Hussain et al. [31] investigated the entropy generation in unsteady MHD mixed convection inside a horizontal channel containing an adiabatic square obstacle with an open cavity heated from below. The cavity filled with Al_2O_3 -Cu-water hybrid nanofluid. Three different vertical locations of the obstacle were considered. They

deduced that the increase in Ri , Re and ϕ boosts the rate of heat transfer and entropy generation. Hussain et al. [32] considered the entropy generation of the mixed convection in an inclined channel with a cavity filled with alumina-water nanofluid saturated in a porous medium. It was observed, that the heat transfer is enhanced by increasing Da , Re and the porosity. Also, it was found that Be increases with increasing Re and porosity, while it declines with increasing Ri . Yasin et al. [33] conducted a numerical and experimental research about the effect of a vertical unheated baffle on the mixed convection of air in an open square cavity attached to a square duct. It was observed that the maximum Nusselt number has occurred at the highest length of the baffle. Sivasankaran et al. [34] portrayed the effect of an adiabatic vertical baffle on the mixed convection in an open. Two different modes of heating (i.e., linearly heating and sinusoidal heating) were imposed. It was found that the sinusoidal heating provides more heat transfer rate than linearly heating. Also, it was shown that by increasing the baffle length, the averaged energy transport inside the channel-cavity assembly is increased. Sabbar et al. [35] analyzed numerically the transient mixed convection in a cavity rectangular-channel assembly due to the interaction between the fluid flow and the elastic walls. They concluded that the heat transfer rate is enhanced about 17% by the existence of the elastic wall(s) compared with rigid walls of the cavity. The numerical investigation of 2D transient mixed convection of air in an open cavity located at the bottom of a channel with different aspect ratios was performed by Carozza [36]. It was found that the assisting configuration was more efficient compared with the opposing one. Abd Al-Hassan and Ismael [37] included the unsteady double diffusive mixed convection in an open cavity located in the bottom of a horizontal channel. One of the vertical sides of the cavity was kept at a constant temperature and concentration, while all other walls were considered impermeable and adiabatic. A porous layer was included in the lower part of the cavity. It was found that for the assisting case Nu and Sherwood number (Sh) decreases with increasing H_p , while their behavior was different with H_p for the opposing case. Contreras et al. [38] carried out experiments of 3D opposing combined convection in an open cubical cavity located at the mid-section of a vertical square channel. A stereoscopic time-resolved particle image velocimetry (TR-PIV) was used to assess the thermal effects on the flow. They concluded that the increase in Re lowers the critical ichardson number above which the flow was no longer encapsulated. Ahmadi and Khosravi [39] involved the non-Newtonian fluid in a 2D laminar mixed convection in a cavity linked with a horizontal channel. A non-Newtonian two phase fluid flow was entered the channel with the cavity. The polymer solution and water were selected as two-phase flow. The results revealed that the changes in the velocity, pressure and volume fraction of fluids inside the channel and

cavity were more sensible to variation in the Re instead of changing the rheological index n .

Table 1 summarizes some of the regular cavities opened to a rectangular channel. The table includes short portray of the tools used in the investigation, the overall geometry, ranges of the studied parameter, fluid type and the main conclusions.

3.2. Mixed convection in complex cavity-channel assembly

For the sake of promoting the convective heat exchange, sophisticated geometries are studied, these including doubling the cavities, driving one or more of the cavity walls, inserting an oscillating baffle, injecting a secondary flow into the cavity and using discrete heating. As an attempt to improve the heat transfer of a grooved channel, Biswas et al. [40] suggested a novel strategy that is dividing the total flow into two flows. The first is the main flow which is flow regularly through the channel while the other is injected from an opening made at the base of the groove. With the aid of an in-house CFD FVM code, they addressed a pronounced augmentation by the injection of the fluid reaches to 141%. After the results achieved by the injection strategy, several geometries were investigated considering natural aspiration (venting fluid by no power) such as; aspiration with the aid of the moving walls [41]; aspiring a cavity involving porous layers [42,43] or protruding a heating element [44] and different configurations of surface heating elements [45]. García et al. [46] performed a numerical 2D transient mixed convection in an inclined rectangular channel containing two facing identical open cavities. They concluded that the heat transfer rate is increased by increasing the Re for fixed values of the Ri . The transient laminar opposing flow mixed convection in an inclined square water-filled channel, which included two symmetric open cubic cavities subjected to a constant wall heat flux was examined experimentally by Cardenas et al. [47]. Particle Image Velocimetry (PIV) was used for the measurements. It was found that the overall heat transfer was a nonlinear function of the channel inclination angle. Laouira et al. [48] presented a numerical simulation about the effects of heat source length on the combined convection in a channel with an open trapezoidal cavity. They concluded that Nu was increased with increasing the length of the heat source. Yaseen and Ismael [49] considered the role of the non-Newtonian FSI in mixed convection in a trapezoidal cavity opened to a horizontal channel. An elastic baffle was fixed at the upper wall of the channel and downwards to the open cavity. They concluded that for low Ri , the shear-thickening fluid manifests higher Nusselt number while for high Ri number, the shear-thinning fluid has the higher values. Yaseen and Ismael [50] extended their work (Ref. [49]) by studying various locations of the baffle (left, center, and right) with respect to the cavity center. They found that the location of the elastic baffle near the channel inlet gives a maximum Nu number. Al-Farhany et al. [51]

Table 1. Summary of classical cavity-channel geometries given in the present review.

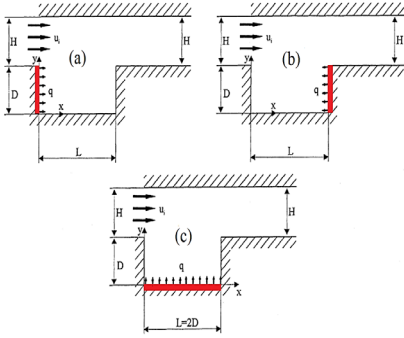
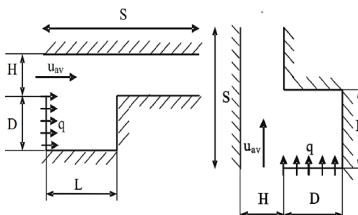
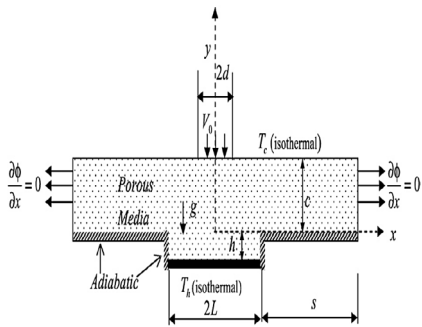
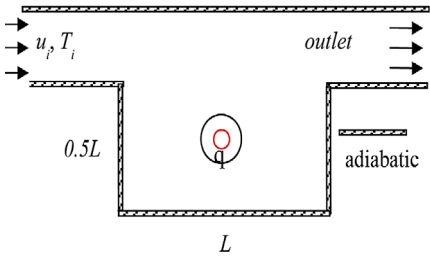
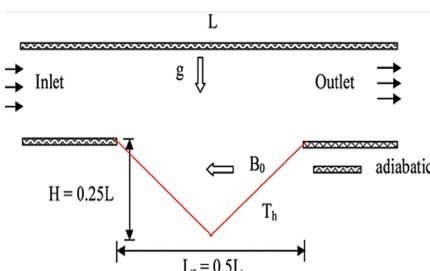
Refs.	Model and method	Geometry	Ranges of variable and working fluid	Conclusions and correlations
Manca et al. [1] 2003	FEM		$100 \leq Re \leq 1000$ $0.1 \leq Ri \leq 100$ $0.1 \leq (H/D) \leq 1.5$ $AR = 2$, Air, $Pr = 0.71$	Assisting case: $Nu = 1.6854 - 0.2164(H/D)$ $-1.933(H/D)^2 + 6.0347(H/D)^3$ $-7.057(H/D)^4 + 3.7348(H/D)^5$ $-0.74775(H/D)^6$ Opposing case: $Nu = 1.1093 + 5.0147(H/D)$ $-10.391(H/D)^2 + 6.9637(H/D)^3$ $+1.5976(H/D)^4 - 3.5819(H/D)^5 +$ $1.0624(H/D)^6$
Buonomo et al. [13] 2008	FVM		$Da = 0.01$ $100 \leq Re \leq 1000$ $0.1 \leq Ri \leq 100$ $H/D = 1$ $AR = 2$ $Pr = 0.71$ Air saturated with a porous medium	The two considered configurations exhibited very similar behaviors for low values of the Ri and Re numbers.
Wong and Saeid [16] 2009	FVM		$50 \leq Ra \leq 150$ $1 \leq Pe \leq 1000$ $0 \leq h/H \leq 0.4$ Air saturated with a porous foam $Pr = 0.71$	Nu increases with the increase of Ra .
Rahman et al. [17] 2012	FEM		$10^3 \leq Ra \leq 10^5$ $0.2 \leq K \leq 50$ $AR = 2$ Different fluids, $0.7 \leq Pr \leq 7$ $Re = 100$	The maximum bulk temperature reduces with increasing the conductivity ratio K and Pr .
Rahman et al. [18] 2012	FVM		$100 \leq Re \leq 2000$ $10^3 \leq Ra \leq 10^5$ $10 \leq Ha \leq 100$ $0 \leq J \leq 5$ Different fluids, $1 \leq Pr \leq 10$	The heat transfer increases by increasing Re and Pr .

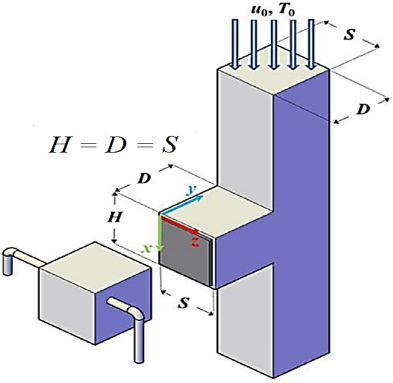
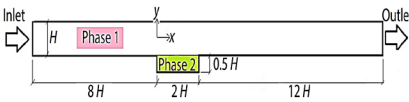
Table 1. Summary of classical cavity-channel geometries given in the present review (continued).

Refs.	Model and method	Geometry	Ranges of variable and working fluid	Conclusions and correlations
Rahman et al. [23] 2014	FEM		$0.1 \leq Ri \leq 10$ $0.01 \leq K \leq 10$ $0.1 \leq D \leq 0.5$ Water, $Pr = 7$	The Nu increases with Ri except at $D = 0.5$, while it decreases with increasing of D .
Mehrez et al. [25] 2015	FVM		$1 \leq Ri \leq 0.04$ $Gr = 10^4$ $100 \leq Re \leq 500$ $0^\circ \leq \gamma \leq 360^\circ$ $0 \leq \phi \leq 0.06$ Cu-Water nanofluid, $Pr = 6.2$	The entropy generation is influenced by the inclination angle γ , Re and ϕ .
Sharma et al. [26] 2015	FVM		$0.01 \leq Ri \leq 1000$ $10 \leq Re \leq 200$ Air, $Pr = 0.71$	With the aid of the baffle, the Nusselt number at $Re = 200$ is enhanced by 25–175%.
Timuralp and Altaç [27] 2016	FVM		$0.1 \leq Ri \leq 10$ $10 \leq Re \leq 200$ $0.5 \leq H / D \leq 2$ $0.5 \leq AR \leq 1$ Air, $Pr = 0.71$	The forced convection becomes dominant at high value of Re .

Table 1. Summary of classical cavity-channel geometries given in the present review (continued).

Refs.	Model and method	Geometry	Ranges of variable and working fluid	Conclusions and correlations
Hussain et al. [31] 2017	FEM		$1 \leq Re \leq 200$ $0.01 \leq Ri \leq 20$ $0 \leq Ha \leq 100$ $0.0 \leq \phi \leq 0.04$ Hybrid nanofluid, Al_2O_3 -Cu-water	The flow is deviated to the channel when Ha number increased.
Hussain et al. [32] 2017	FEM		$10 \leq Re \leq 200$ $0.01 \leq Ri \leq 20$ $0.0 \leq \phi \leq 0.04$ $10^{-6} \leq Da \leq 10^{-3}$ $0^\circ \leq \gamma \leq 360^\circ$ Al_2O_3 -Water $Pr = 6.2$ $Porosity = 0.2 - 0.8$	Bejan number increases with increasing Re and porosity, while it decreases with increasing Ri .
Yasin et al. [33] 2018	Experimental, ANSYS-FLUENT		$300 < Re < 1000$ $1.2 \times 10^7 < Gr < 8.3 \times 10^7$ $250 < Re < 1400$ $1.0 < Ri < 700$ $q'' = 300 \text{ and } 500 \text{ W/m}^2$ $Air, Pr = 0.7$	The maximum Nu is recorded at the highest length of the baffle.
Sabbar et al. [35] 2018	(ALE) with FEM		$10^{-5} \leq Ca \leq 10^{-3}$ aspect ratio, $D/H = 1$ cavity width $Lc/H = 2$ $Le/H = 3$ $0.1 \leq Ri \leq 100$ $50 \leq Re \leq 250$ $Air, Pr = 0.71$	The heat transfer is enhanced by about 17% by the existence of the elastic wall.
Abd Al-Hassan and Ismael [37] 2019	FEM		$0.01 \leq Ri \leq 100$ $10 \leq Re \leq 200$ $0.25 \leq Hp \leq 1$ $Da = 10^{-3}, N = 0$ $Le = 20$ Water Saturated with a porous medium $Pr = 6.26$	For the assisting case, Nu and Sh numbers decrease with increasing Hp .

Table 1. Summary of classical cavity-channel geometries given in the present review (continued).

Refs.	Model and method	Geometry	Ranges of variable and working fluid	Conclusions and correlations
Contreras et al. [38] 2019	POD		$Re=1500$ and 4500 $0 \leq Ri \leq 20$ $Gr = 4.05 \times 10^6$ and 4.5×10^7 Water, $Pr=7$	The increase in Re decreases the critical value of Ri , above which the flow is no longer encapsulated.
Ahmadi and Khosravi [39] 2020	FVM		$500 \leq Re \leq 1500$ $\rho=800 \text{ kgm}^{-3}$, $\lambda = 0.036 \text{ s}$ $\mu_0 = 0.00345 \text{ kgm}^{-1}\text{s}^{-1}$ $\mu_\infty=0.056 \text{ kgm}^{-1}\text{s}^{-1}$ $AR=4$ non-Newtonian two-phase fluid-flow $0.7 \leq n \leq 1$	The changes in the velocity, pressure and volume fraction of fluids inside the channel and cavity are more sensible to Re .

showed the effect of discrete heat source on the combined convection inside a channel with an open complex cavity. A magnetic field was applied to the assembly from its right side. They deduced that Nu was increased with the increase of Ri and decreases with Ha . Ismael et al. [52] performed a study of the combined convection of air in a horizontal channel with a heated trapezoidal cavity of moving walls. Four different cases were studied depending on the movement of the cavity sidewalls. They studied the effects of Ri and Reynolds number ratio (Re_r) on the flow and thermal fields. They concluded that, the Nu increases with the increase of the Ri and Re_r . Mebarek-Oudina et al. [53] developed the study of Ismael et al. [52] by considering two discrete heaters rather than one on the base of the trapezoidal cavity. The notation of the four cases were also adopted exactly as in Ref. [52]. The sole result they found are that the role of Heater 2 is more pronounced in the case of single moving wall, while Heater 1 gets active when two sidewalls are in a movement, Case II. Sachica et al. [54] dealt with the transient MHD mixed convection and entropy generation of Al_2O_3 -water nanofluid in a rectangular vertical channel with two facing identical open cubic cavities with discrete heating. Their conclusions were that the increase in the nanoparticle volume fraction ϕ , the entropy generation decreases with the magnetic field for all ranges of Ri and Ha . Based on the feasibility of implementing flexible baffles in augmenting the heat transfer, Yaseen and Ismael [55] focused on the stress and the deflection in a baffle used in promoting the heat transfer in a trapezoidal cavity opened to a

rectangular channel considering a power law fluid flow. Their results highlighted the decrease of von Mises stresses with Re for fluids of power law index n less than unity, while for $n > 1$, von Mises stresses increase with Re . In addition, they added that the flexible baffle exhibits lower stresses than rigid baffle. As an extension to their work, Abd-Al-Hassan and Ismael [56] promoted their previous work [37] by inclining the porous layer. They indicated that the heat and mass transfers of the inclined porous layer could be 30% and 32%, respectively greater than the horizontal layer. Some of the reviewed works in this section are summarized in Table 2.

3.3. Numerical methods adopted in mixed convection

The non-linearity of the equations that govern the mixed convection becomes more influential due to the convective terms in the momentum and energy conservation equations, (and the mass conservation equation if the advection is considered). Therefore, attention should be focused on the stability of the numerical solution of such equations. The review has discovered more than one numerical strategies are available with mixed convection. The most strategy used is the FVM where about 56% of the numerical studies have followed the FVM. This is because such a method is built on the basis of integrating the conservation equations. Therefore, the convergence of the solution is mostly guaranteed while the pressure gradient term is successfully corrected using the SIMPLE algorithm. The FEM is also followed but because its complexity and the required storage

Table 2. Summary of complex cavity-channel geometries given in the present review.

Refs.	Model and method	Geometry	Ranges of variable and working fluid	Conclusions and correlations
Biswas et al. [40] 2015	FVM		$0.1 \leq Ri \leq 10$ $50 \leq Re \leq 200$ $0 \leq Pj(\text{jet position}) \leq 0.95$ $0.01 \leq Wj(\text{injection width}) \leq 0.2$ $10\% \leq qj(\text{injection ratio}) \leq 50\%$ Air, $Pr = 0.71$	Dividing the total flow to main and injected flows augments Nu by 218%. The injection becomes more effective when it is located close to the hot wall. The width of the injection acts adversely on the Nusselt number.
García et al. [46] 2019	FVM using Open-MP		$100 \leq Re \leq 1000$ $0^\circ \leq \gamma \leq 90^\circ$ $0.25 \leq AR \leq 1$ Water, $Pr = 7$	The heat transfer rate increases by increasing the Re .
Cárdenas et al. [47] 2019	Experimental		$32.17 \leq Ri \leq 300.77$ $0^\circ \leq \gamma \leq 90^\circ$ $500 \leq Re \leq 1500$ $H = S = W = D = 5 \text{ cm}$ $\text{Length}(T\text{-section}) = 180 \text{ cm}$ Water, $Pr = 7$	The overall heat transfer was a nonlinear function of the inclination angle. For left cavity wall (Roof) at $Re = 1000$: $Nu = 0.63736Gr^{0.21111}$ For right cavity wall (floor) at $Re = 1000$: $Nu = 0.7763Gr^{0.20138}$
Laouira et al. [48] 2020	ANSYS		$0.16 \leq \text{Heat source length} \leq 1$ $0.1 \leq Ri \leq 100$ $Re = 100$ Air, $Pr = 0.71$	Nu increases with increasing the length of the heat source.
Yaseen and Ismael [49] 2020	FEM		$10^{-20} \leq Ca \leq 10^{-3}$ $100 \leq Re \leq 300$ $0.01 \leq Ri \leq 10$ Power law Fluid $0.5 \leq n \leq 1.5$	For low Ri , the shear-thickening fluid manifests higher Nu number while for high Ri number, the shear-thinning fluid has the higher values.

Table 2. Summary of complex cavity-channel geometries given in the present review (continued).

Refs.	Model and method	Geometry	Ranges of variable and working fluid	Conclusions and correlations
Al-Farhany et al. [51] 2020	COMSOL multiphysics		$Re = 100$ and 150 $0.1 \leq Ri \leq 10$ $0 \leq Ha \leq 15$, Air, $Pr = 0.707$.	Nu increases with the increase of Ri and the decrease of Ha .
Ismael et al. [52] 2020	FEM		$Re = 100$ $0 < Re_r < 5$ $0.1 < Ri < 100$ Air, $Pr = 0.71$	The maximum Nu occurs with case I.
Sáchica et al. [54] 2020	CVM		$0 \leq Ha \leq 0$ $-1 \leq Ri \leq 5$ $0.0 \leq \phi \leq 0.2$ $100 \leq Re \leq 700$ Al_2O_3 – water nanofluid	Nu decreases with the increase of Ha for all values of Re .
Abd Al-Hassan and Ismael [56] 2022	FEM		$50 \leq Re \leq 250$ $0.1 \leq Ri \leq 100$ $0.25 \leq Hp \leq 1$ $Da = 10^{-3}$, $Le = 20$, and $N = 0.5$ Porous medium, $Pr = 6.24$	The opposing case is better than the assisting case The heat and mass transfers of the inclined porous layer are 30% greater than the horizontal layer. Assistance case: $Nu = \begin{cases} 0.187 Re^{0.645} Ri^{0.232} \\ 0.159 Re^{0.632} Hp^{-0.162} \end{cases}$ Opposing case: $Nu = \begin{cases} 0.451 Re^{0.553} Ri^{0.22} \\ 0.875 Re^{0.359} Hp^{0.033} \end{cases}$

capacity needed, the studies using FEM is about 29% of the total numerical studies. The FEM is recalled when there is an interaction between the fluid and the structure. On the other hand, the Finite Difference Method (FDM) and the LBM are rarely used in channel-cavity assembly because these methods fail in representing the complex boundaries. Proper Orthogonal Decomposition (POD) method is one of the rarely used method.

The percentage of studies dealing with FDM, LBM, and POD are 5% for each. Figure 2 portrays the percentage of papers that uses each numerical method.

3.4. Experimental techniques used in mixed convection

The experimental studies of mixed convection in a cavity channel assembly are scare compared with the numerical papers.

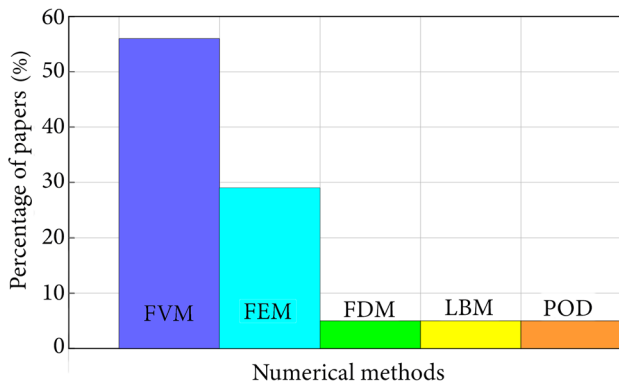


Figure 2. Percentage of numerical works against the numerical method used.

papers. This is mainly because of the experimental investigations deals with real cases rather than assumptions. For example, to preserve a steady flow condition, the test section should be provided by liquid from a constant-head tank which in turn is fed by fluid from another large tank [38]. This cycle is attained by a suitable pump. If the fluid is gas, care must be taken in designing the ducting to avoid the vortices created when air enters to sudden duct. Moreover, flow straightener is necessary prior to the test section to bring uniform steady flow. Another example of the real complication of the experimental work is the effort of maintaining a constant surface temperature, the case which need extra heat exchanger and a circulating pump and a heat transfer fluid to maintain constant wall temperature. Furthermore, in numerical simulation, the results are displayed by several commercial software with a wide range of facilities and presentation, whereas the experimental results are collected using an expensive instrumentation like the PIV.

4. Conclusions

The current paper reviews and categorizes some results of researches conducted on mixed convection in an open cavity connected with rectangular channel. This compilation serves a broad spectrum of scientific and engineering fields where the knowledge of mixed convection in enclosures is applied. The reviewed works have been classified into two main categories, regular and complex geometries. With “complex geometry” we put the double-faced open cavity, baffled cavities, wall(s) driven cavities and partially layered open cavities.

4.1. Summary of the findings

It is found that the best geometry that gives maximum heat and mass transfer is that when the source of heat and species is located at a vertical wall of the cavity where it opposes the direction of the flow in the channel. The key parameter in such a geometry is the Reynolds number which notably augments the mixed convection in all conditions. It is found that as shown in Figure 3, the complex geometries comprise 20% of the reviewed papers. The review has revealed that (as shown in Figure 4) the experimental studies are relatively

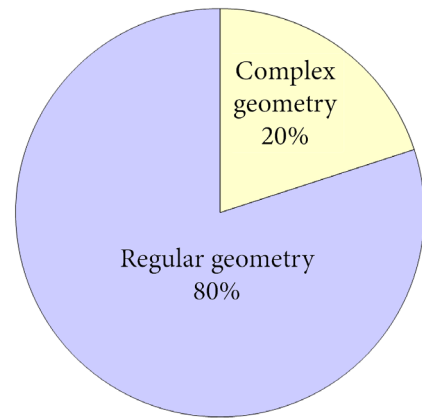


Figure 3. Percentages of the regular and complex geometries of the cavity-channel assembly.

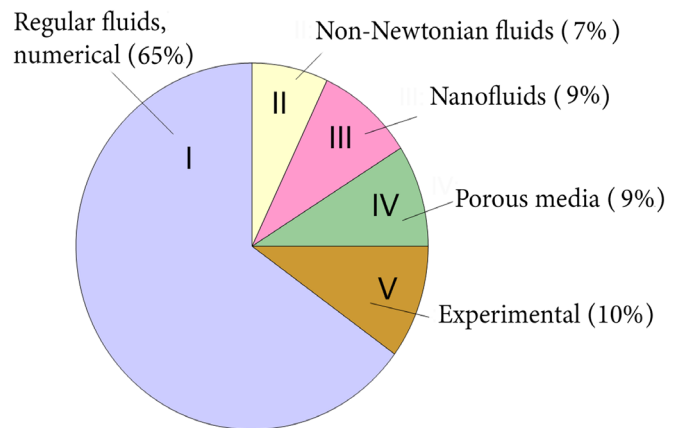


Figure 4. Percentages of different studies.

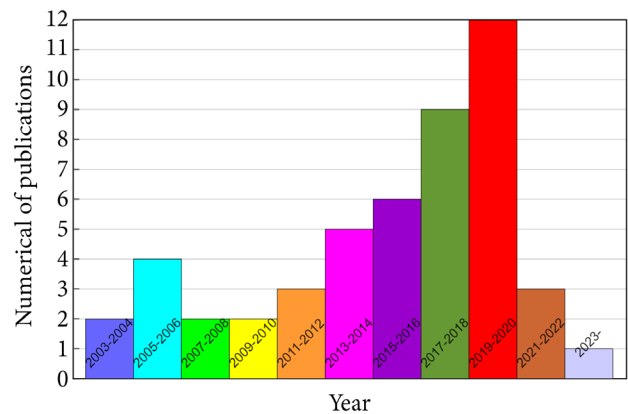


Figure 5. Number of published papers arranged chronologically.

scarc where it comprises only 9% of the total reviewed studies. This can be returned to the intricacy of the experimental work. On the other hand, published studies dealing with nanofluids and porous media filling cavities are 9% for each. The nanofluids studies, however, are also few compared with the overall reviewed papers. Eventually, Figure 5 portrays the number of published papers arranged chronologically. The figure emerges that the topic under study has been started two decays ago. In the second decay, the works are increased notably. However, the maximum number of published papers is recorded within 2019 to 2020.

4.2. Future topics

Although the topic of mixed convection in channel-cavity assembly is interesting and widely investigated, the following topics are not found in the open literature, thus it is suitable to be addressed in the future works:

- (i) Studying the contamination removing from the cavity i.e., studying the equation of mass transfer;
- (ii) The process of injection or aspiration of the flow from the bottom or sides of the cavity, which gives a promised improvement of heat and mass transfer.

Nomenclature

A	Velocity amplitude ratio
AR	Aspect Ratio (width/height)
Bi	Biot number
Ca	Cauchy number
Da	Darcy number
Gr	Grashof number
Ha	Hartman number
J	Joule heating parameter
K	Conductivity ratio
N	Buoyancy ratio
n	Power law index
Nu	Average Nusselt number
Le	Lewis number
Pr	Prandtl number
q''	Heat flux
Re	Reynolds number
Re_r	Ratio of Reynolds numbers
Ri	Richardson number
Sc	Schmidt number
Sh	Sherwood number
Str	Strouhal number

Abbreviations

MP	Multi-Processing
TR	Time Resolved
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
PFV	Parallel Finite Volume
FEM	Finite Element Method
FVM	Finite Volume Method
FDM	Finite Difference Method

Greek symbols

ϕ	Nanoparticles volume fraction
γ	Inclination angle of the assembly

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution

A. Kadhim Hussein: Conceptualization;
A. Abdul Razaq Abdul Hussein: Formal analysis and investigation; Writing - original draft preparation;
A. Abidi: Funding acquisition;
M.A. Ismael: Methodology;
A.B. Mahdi and B.S. Bashar: Resources;
R.Z. Homod, O. Younis, F. Lafta Rashid: Writing - review and editing;
L. Kolsi: Supervision;
A.J. Chamkha: Supervision and revision.

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