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Research paper

Heat transfer characteristics and entropy generation in cascaded air cavity

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Abstract

In reality every thermodynamic process is an irreversible process. All sort of processes have this kind of macroscopic and microscopic energy loss. Every system in a thermodynamic process generates finite amount of entropy. The entropy generation is presently studied for vertical cavity with different configurations. The effect of cavity walls temperature difference, cavity cascading, and cascading positions on the overall values of entropy generation are investigated and reported. An important analogy between this work and thermodynamic analysis of Carnot is observed.

Keywords: *CFD; Cavity; Entropy Generation; Natural Convection; Heat; Thermodynamic.*

1. Introduction

Natural heat convection in cavities has been extensively studied because of its importance in different engineering applications. Physically, entropy is a disorder of a system and its surrounding. Basically on a microscopic level, it occurs when heat transfer takes place because heat is energy and when it moves some additional movements happen, e.g, molecular friction, molecular vibration, internal displacement of molecules, spin moment, kinetic energy etc which cause loss of useful heat thus heat cannot be transformed fully into work. These additional movements create chaos in the system and surroundings. That is why some times entropy is called the measure of chaos or randomization. This microscopic chaos results in a macroscopic level disorder which occurs because of some unnecessary irreversibilities e.g. friction, unstained expansion, mixing of fluids, electric resistance, inelastic deformation of solids, chemical reaction, and unnecessary heat transfer in finite temperature difference. Noted that such kind of energy loss cannot be regained so the system and surrounding cannot come to its initial state without extra work exerted on it. Therefore entropy is called the measure of irreversibilities . For this reason, heat energy cannot be converted totally into work .
Reference [1] analyzed the entropy generation caused by free convection in an enclosure heated locally from below with two isoflux sources. In Ref. [2], entropy generation in rectangular cavities with identical areas but different aspect ratios is studied. The work in Ref.[3] presents a CFD study of entropy generation in rectangular cavities under natural convection process. Five aspect ratios, five Rayleigh numbers, and four irreversibility coefficients are considered. Reference [4] investigated the entropy generation due to heat transfer and friction in transient state for laminar natural convection. In Ref.[5], entropy generation for natural convection in a partitioned cavity, with adiabatic horizontal and isothermally cooled vertical walls, is studied numerically by both a FORTRAN code and the commercially available CFD-ACE software. CFD prediction of local and global entropy generation rates in free convection in a vertical channel symmetrically heated at uniform heat flux are presented [6]. CFD predictions of entropy generation in turbulent natural convection due to internal heat generation in a square cavity are reported for the first time [7]. An enhanced cell-centered finite-volume procedure was expressed for solving the natural heat convection of the laminar air flow in a Γ -shaped enclosure with circular corners [8]. A design is given of plate finned heat sinks by minimizing their rates of entropy generation [9]. Natural convection in a vertically concentric annular space of practical importance and has been investigated [10]. Entropy generation due to natural convection has been calculated for three radii and a wide range of Rayleigh numbers for an isothermal cylinder [11] and [12].
In the present study, the entropy generation is studied for a vertical cavity with different configurations. The effects of cavity wall temperature difference, cavity cascading, and cascading position on the overall values of entropy generation are reported. An important analogy between this work and thermodynamic analysis of Carnot is observed.

2. Numerical modeling

The geometry of the theoretical model and the boundary conditions are illustrated in Fig. 1. The model is a rectangular tall cavity of (20 cm×200 cm). The right wall temperature is 350 K while the left wall temperature is 300 K as shown in Table 1. Both the top and bottom walls of the cavity are considered adiabatic. The thermal and flow fields are calculated numerically with commercial CFD software ANSYS FLUENT 18.1. The flow is assumed steady state, incompressible, and turbulent. The fluid and the solid properties are assumed constant. The effects of gravitation are considered and thermal radiation is neglected. Buoyancy effect is modeled using Boussinesq approximation. Thermophysical properties are assumed constant elsewhere. The equations adopted in the present model are

$$\frac{\partial}{\partial x_i}(\rho v_i) = 0.0 \quad (1)$$

$$\frac{\partial}{\partial x_j}(\rho V_i V_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial \tau_j} \quad (2)$$

$$\frac{\partial}{\partial x_i}(V_i(\rho E + P) = -\frac{\partial}{\partial x_i}\left(K\frac{\partial T}{\partial x_i}\right) \quad (3)$$

Where, i is a tensor indicating 1, 2, and 3, and $\tau_{ij}$is the viscous stress tensor. The variables $V, P, T,$ and E are the air flow velocity, pressure, temperature, and energy, respectively.The entropy generation is associated with the heat transfer and the fluid flow friction. The local entropy generation (S_l) can be determined by the following expression

$$S_l = \frac{K}{{T_o}^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left[\left(\frac{\partial T}{\partial y}\right)^2\right]\right] + \frac{\mu}{T_o}\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right] \quad (4)$$

Where, K is the air thermal conductivity, T_o is the cavity operating temperature, and μ is the air dynamic viscosity. The variables u and v are the flow velocities in the x and y directions, respectively. The first term of this equation represents the entropy generation due to heat transfer while the second term represents the entropy generation due to the viscous effects of the flow. The local total entropy generation can be expressed as

.

$$S_l = S_{lh} + S_{lf} \quad (5)$$

Where S_{lh} and S_{lf} are the local entropy generation due to heat transfer and fluid flow respectively. The total entropy generation is obtained through the integration of the local entropy generation for all the computational domain

$$S_T = \iint S_l \, dA \quad (6)$$

An alternative parameter for irreversibilities distribution is the Bejan number (Be) defined as

$$Be_l = \frac{S_{lh}}{S_{lh} + S_{lf}} \quad (7)$$

While the average Bejan number in the computational domain is expressed as

$$Be_T = \frac{S_{Th}}{S_{Th} + S_{Tf}} \quad (8)$$

Where S_{Th} and S_{Tf} are the total entropy generation due to heat transfer and fluid flow respectively.

Table 1: Boundary Conditions

Walls temperature difference	10, 20, 30, 40, and 50 °C
No. of cascading	1, 2, and 3
Cascade position	B/3, (2B/3)
Right and left wall temperature	350, and 300 K

RNG K−ε RNG K - ε turbulent model was utilized to solve the complicated turbulent thermal flow field with enhanced wall function approach in the near-wall regions to fit the wall boundary conditions. The solution convergence was considered when the scaled residual of the energy equation reached 10^{-7} and the scaled residuals of other equations reached 10^{-4}.

3. Mesh Generation, Discretization, and Verification

The geometry depicted in Fig. (1) and the mesh of the computational model are generated separately using GAMBIT 2.4.6. Structured meshing scheme is used. In order to test the dependence of the numerical results on the grid density, calculations are carried out with different mesh densities in the X and Y directions. The first grid points adjacent to the walls are kept at y+ values between 1 and 5. The computational results of the entropy generation of the cavity varied to give about 1% deviation when the number of grids increased from 128,340 to 194,960. When the grid size increased from 194,960 to 224,960 only 0.02% variation in entropy generation was obtained.

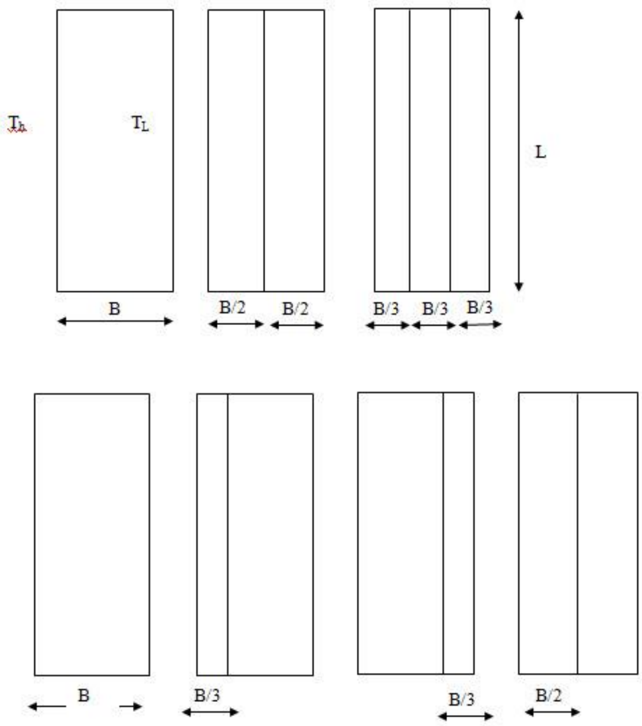

Fig. 1: Simulation Domain and Boundary Condition.

The comparison of experimental and CFD results for a rectangular cavity of 2 m length and 0.078 m width [12] is revealed in Fig. (2). The comparison between the velocity distribution at the mid height of the cavity shown in Fig. (2) exhibits a good agreement between the present work and the experimental data in Ref. [12]. The air velocity increases at the cavity walls due to the effect of bouncy force and the changes of air temperature and density close to the cavity hot and cold walls. The air velocity is upward on the hot wall and becomes downward on the cold wall as seen in Fig.(2). The effect of continuity equation residual is shown in Table 2. The mass imbalance decreases and the cavity maximum speed becomes constant when the continuity equation residual becomes 1E-04 as illustrated in Table 2.

Table 2: Effect of Continuity Equation Residual

Residual of continuity equation	Cavity maximum velocity
1E-02	0.3213321
1E-03	0.3213231
1E-04	0.3213231
1E-05	0.3213231
1E-06	0.3213231

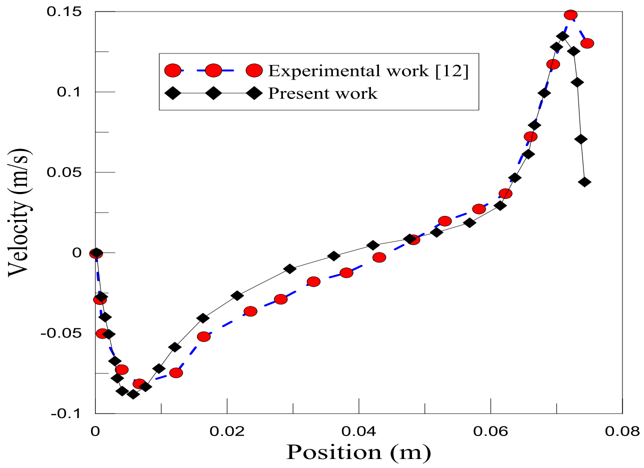

Fig. 2: Comparison of Experimental and CFD Velocity Distribution at Cavity Mid-Height.

4. Results and Discussion

There is an analogy between the air cavity and the well known Carnot cycle. The evolution of a fluid packet through the closed cavity that guides the flow loop is similar to the conventional Carnot cycle. Starting from the bottom of the heated wall, the fluid is heated by the wall and expands as it rises to the cavity top wall. Later, along the down flowing branch of the cycle, the fluid packet is cooled by the cavity cold wall and compressed as it reaches the cavity bottom wall. From the circuit executed by every fluid packet, it can be noticed that the loop-shaped flow is the succession of four processes, heating → expansion → cooling → compression. One can make an analogue between cavity with two adiabatic walls and two isothermal walls with different temperatures.

Figures (3) and (4) illustrate the entropy generation as a function of cavity walls temperature difference. The amount of heat entropy generated within the cavity increases as the cavity walls temperature difference increases. Temperature gradient is the main source of entropy generation inside the cavity. Heat transfer across finite temperature difference initiate entropy due to heat transfer. Like the previous case, a finite velocity gradient produces entropy due to friction between fluid layers. The ordered kinetic energy of the flow is being dissipated by the effect of temperature and velocity gradient inside the flow and loss of available energy occur.

Figures (5) and (6) demonstrate the effect of dividing the cavity into two small cavities on heat and total entropies, respectively. The position of the cascading wall has an important effect on the amount of entropy generation. Temperature and velocity gradient distributions change with the position of cascading wall . As the cascade wall position moves close to the high temperature cavity wall, the overall cavity temperature gradient decreases and hence the entropy goes down. There is an important analogy between these cases and cascading Carnot cycle into two or more cycles.

Figures (7) and (8) depict the effect of the number of cavity cascading on the values of heat and total entropy, respectively. The cavity under consideration is being divided into two and three small cascaded cavities and the entropy generation is reported for these cases. As the number of cavities increases, the entropy generation decreases. Both velocity and temperature gradients decrease for cascaded cavity and the fluid dissipation function and the heat entropy decreases.

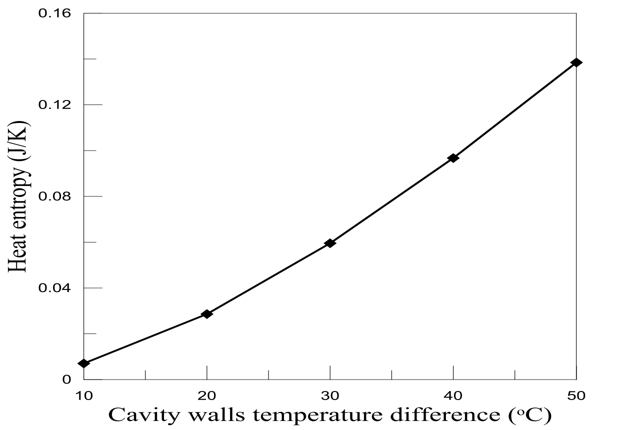

Fig. 3: Entropy Generation Due to Heat Transfer as a Function of Cavity Temperature Difference.

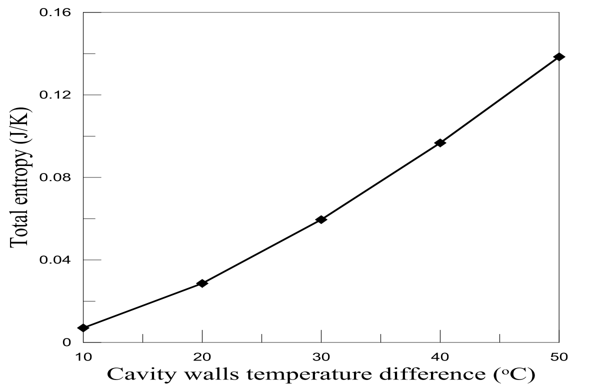

Fig. 4: Total Entropy Generation Due to Heat Transfer Fluid Friction as A Function of Cavity Temperature Difference.

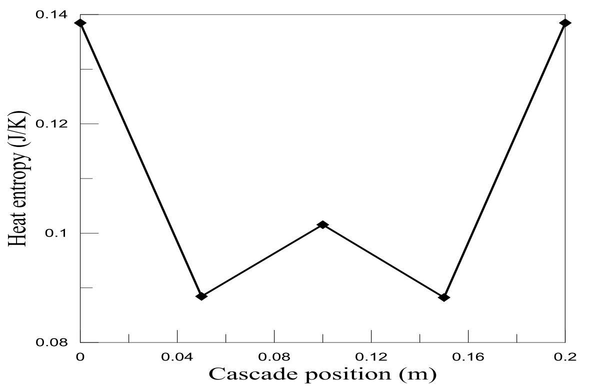

Fig. 5: Entropy Generation Due To Heat Transfer as a Function of Cascading Position inside the Cavity.

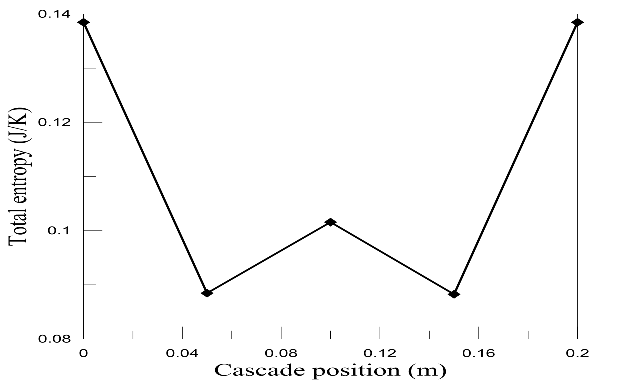

Fig. 6: Total Entropy Generation Due to Heat Transfer and Friction as a Function of Cascading Position inside the Cavity.

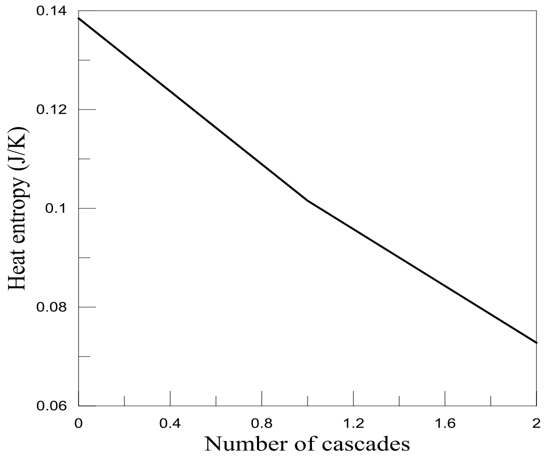

Fig. 7: Entropy Generation Due to Heat Transfer as a Function of Number of Cavity Cascading.

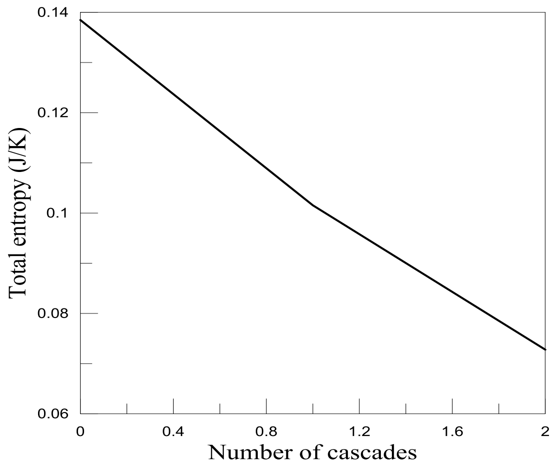

Fig. 8: Total Entropy Generation Due to Heat Transfer and Friction as a Function of Number of Cavity Cascading.

Figures (9 - 26) present the two dimensional distribution of the gauge pressure in (Pa) , temperature in (K), and velocity in (m/s) for all cases under consideration. These plots have been presented as an explanation of how the gradients of the flow variables in both directions change for all cases under consideration. Surface integrations of theses gradients result in the global values of entropy generation.

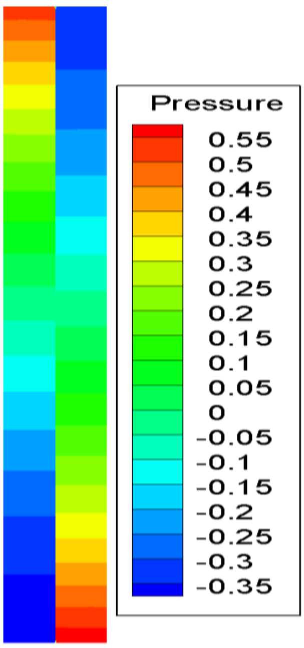

Fig. 9: Pressure Distribution for One Cascade Cavity.

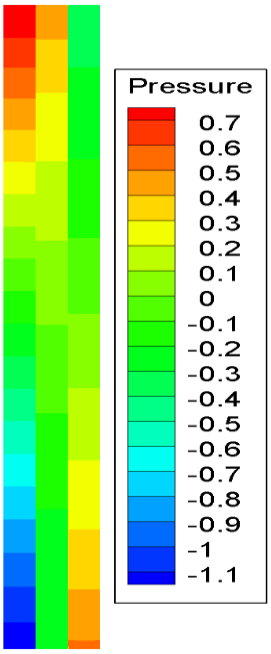

Fig. 10: Pressure Distribution for Two-Cascade Cavity.

So, keeping the fluid flow and heat transfer processes to occur under smooth and low velocity and temperature gradients means low entropy generation inside the flow. As the temperature difference across the cavity increases the total entropy generation increases and the pressure and ordered energy of the flow is being dissipated and transformed into thermal energy. Dividing the cavity into more small cavities results in a smooth temperature and velocity gradient and therefore the fluid dissipation function diminishes and the generated entropy decreases. The position of the dividing wall that split the cavity is very important as can be depicted from the two-dimensional contour plot of fluid and heat transfer parameters.

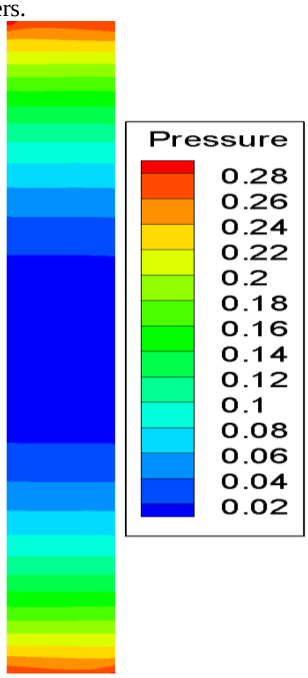

Fig. 11: Pressure Distribution for the Base Cavity.

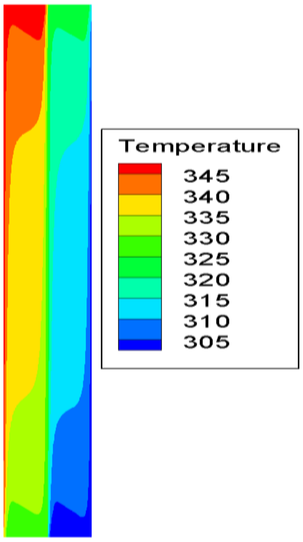

Fig. 12: Temperature Distribution for One Cascade Cavity.

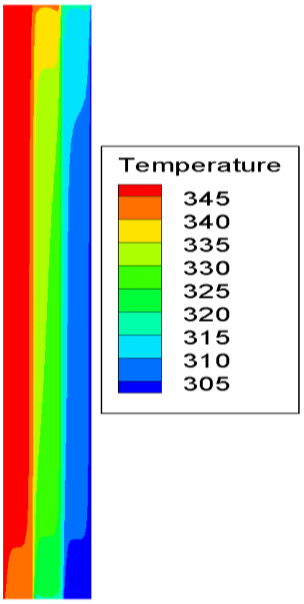

Fig. 13: Temperature Distribution for Two Cascade Cavity.

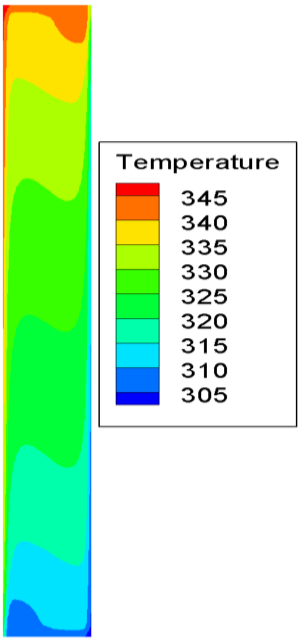

Fig. 14: Temperature Distribution for the Base Cavity.

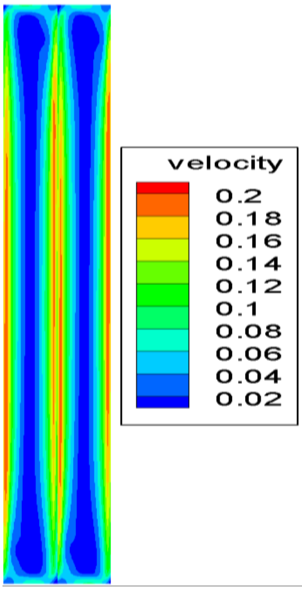

Fig. 15: Velocity Distribution for Two-Cascade Cavity.

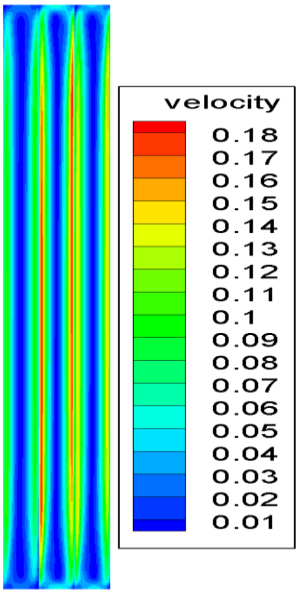

Fig. 16: Velocity Distribution for Two-Cascade Cavity.

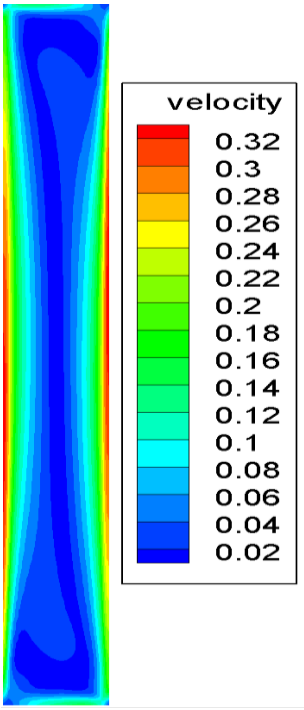

Fig. 17: Velocity Distribution for the Base Cavity.

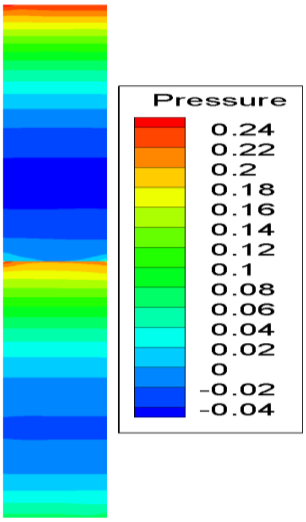

Fig. 18: Pressure Distribution for One Horizontal Cascade Cavity.

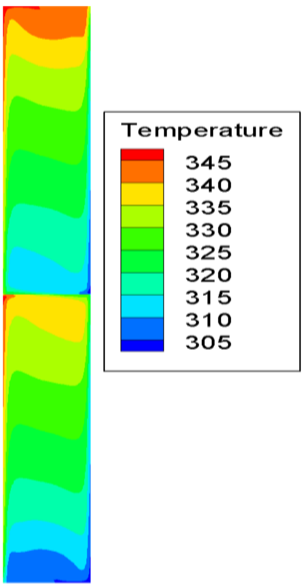

Fig. 19: Temperature Distribution for One Horizontal Cascade Cavity.

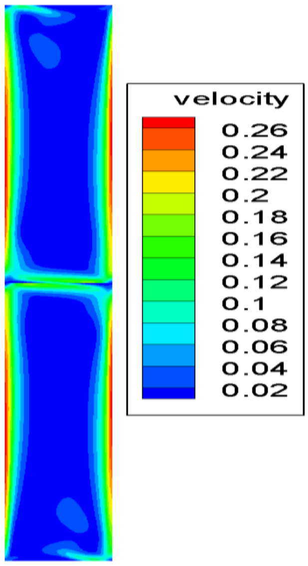

Fig. 20: Temperature Distribution for One Horizontal Cascade Cavity.

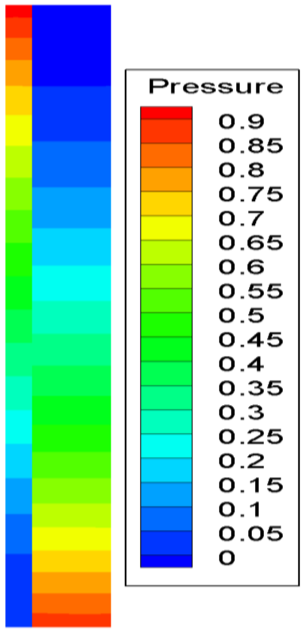

Fig. 21: Pressure Distribution for One Cascade Cavity with Separating Wall Close to the High Temperature Wall.

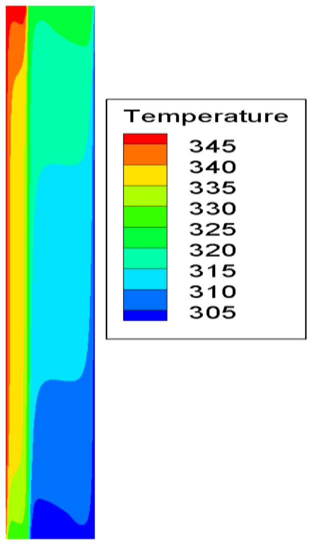

Fig. 22: Temperature Distribution for One Cascade Cavity with Separating Wall Close to the High Temperature Wall.

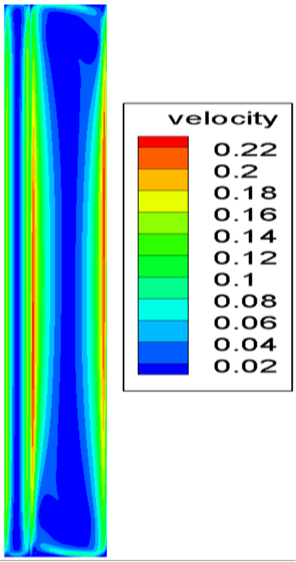

Fig. 23: Velocity Distribution for One Cascade Cavity with Separating Wall Close to the High Temperature Wall.

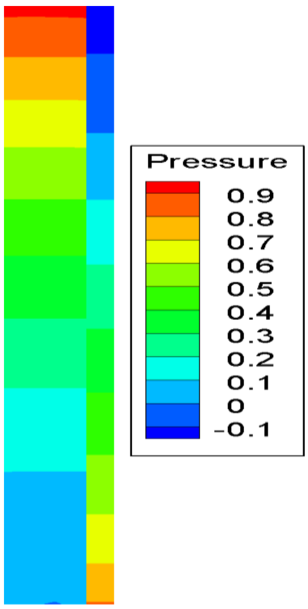

Fig. 24: Pressure Distribution for One Cascade Cavity with Separating Wall Close to the Low Temperature Wall.

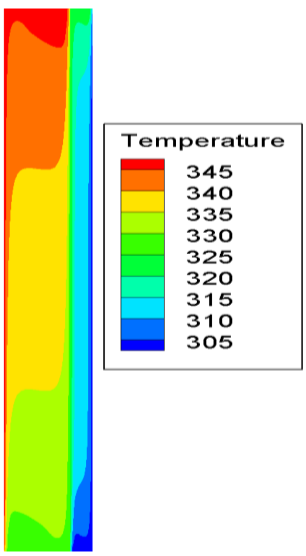

Fig. 25: Temperature Distribution for One Cascade Cavity with Separating Wall Close to the Low Temperature Wall.

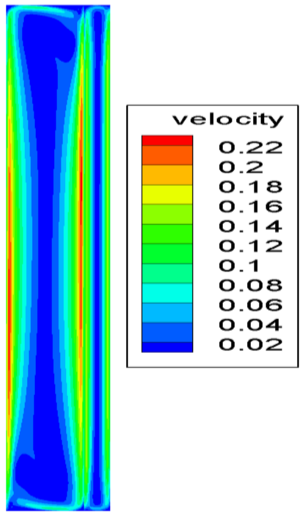

Fig. 26: Velocity Distribution for One Cascade Cavity with Separating Wall Close to the Low Temperature Wall.

5. Conclusions

In real life, all sort of thermodynamic processes have this kind of macroscopic and microscopic energy entropy loss. So in reality each and every thermodynamic process is an irreversible process. Every system in a thermodynamic process, generates a finite amount of entropy. The entropy generation is studied for a vertical cavity with different configurations. The effects of cavity wall temperature difference, cavity cascading, and cascading position of the overall values of entropy generation are furnished. An important analogy between this work and thermodynamic analysis of Carnot is demonstrated.

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