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Numerical Investigation on Oscillation Behavior of a Non-isothermal Self-excited Jet in a Cavity: The Effects of Reynolds Number and Temperature Differences

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P A P E R I N F O	*A B S T R A C T*
	A self-excited oscillating jet can be naturally produced by discharging a plane jet into a rectangular cavity due to pressure effects and without a need for external aid. In recent years, the self-oscillatory jet in non-isothermal conditions has attracted research interests because of its wide range of industrial applications. Therefore, the current study aimed to compare the oscillatory behavior of downward vertical self-excited jet with Reynolds number (*Re*) 1000 and 3000 under various temperature differences (0, 100, and 300 K) between inletflow and cavity's wall. Computational solutions were obtained using unsteady Reynolds averaged Navier-Stokes (URANS) and energy equations for an incompressible flow. The numerical simulation was carried out by the finite-volume based tool OpenFOAM code. The results showed that depending on the value of temperature difference, oscillatory and non-oscillatory flows were observed. Also, at *Re*=3000, the temperature differences can change oscillation frequency up to 10% compared to isothermal conditions. This value reaches 58% at *Re*=1000. The results indicated that where the Archimedes number is less than 0.1, the effects of temperature differences between jet and cavity walls on the oscillating behavior are negligible.

NOMENCLATURE

Ar	Archimedes number	v	Velocity component in y direction (m/s)
Co	Courant number	W	Width of cavity (m)
e	Thickness of nozzle (m)	x, y	Cartesian coordinate
FFT	Fast Fourier Transform	**Greek Symbols**	
f	Frequency (Hz)	α	Thermal diffusivity (m^2/s)
g	Gravity (m/s^2)	β	Thermal expansion coefficient (1/K)
k	Turbulence kinetic energy (m^2/s^2)	ν	Kinematic viscosity (m^2/s)
L	Length of cavity (m)	ρ	Density (kg/m^3)
P	Static pressure (Pa)	ω	Specific of dissipation rate (1/s)
Re	Reynolds number	**Subscripts**	
T	Temperature (K)	0	Jet inlet
t	Time (s)	c	Cavity
u	Velocity component in x direction (m/s)	eff	Effective

1. INTRODUCTION

Jet impingement is used in industrial applications such as cooling and heating processes because it provides a high heat transfer rate between walls and fluid [1]. It is desirable to develop the efficient cooling techniques to ensure performance and reliability of electronic devices [2]. Applying excited jets in the impinging flow can enhance thermal efficiency because their oscillating motion covers a much larger region of impingement

surface than steady jets [3]. The other significant feature of an excited jet is greater mixing rate with higher entrainment that can be used with advantage in combustion and cooling processes [4]. Several methods can excite the jet's flow. They can be classified into passive, active, and hybrid methods. In the passive technique, the jets become excited naturally and do not consume extra energy, so they are called self-excited jets. While, the active methods require an auxiliary device such as a fan, pump, or moving part for jet excitation. Therefore, the passive methods are more affordable and reliable than the active ones. Also, the hybrid methods combine two or more passive and/or active systems [5]. The passive methods attract the attention of engineers and researchers because of their simplicity, low maintenance, and cost. The passive self-exciting jets strongly depend on their geometric structures [6]. Many structures have been developed for self-excited jets, including annular, swirling, and sweeping jets [5].

The present study has considered one of the simplest geometry of a self-excited oscillating jet comprised of a planar jet discharged into a rectangular cavity (Figure 1). These oscillations are driven by the jet deflection mechanism produced by the pressure variations (Coanda effect) [6]. Shakouchi et al. [7] found that a pair of vortices formed on both sides of the jet has an essential role in oscillatory behavior. This self-excited oscillating jet can be operated as an impingement jet for intensifying heat transfer in various applications such as freezing of tissue, drying processes of textiles and paper, cooling of electronic components [3], heat treatment of different metals [5], film cooling, and food processing [8]. These various applications have led to numerous studies on the self-excited oscillating jets. Mataoui et al. [9] numerically and experimentally studied the interaction of a turbulent plane jet issuing into a rectangular cavity under isothermal conditions. They varied jet location inside the cavity and Reynolds number (*Re*) to observe jet oscillation frequency changes. They showed that oscillation frequency increases with Re and height of the jet exit and is decreased by increasing the distance between nozzle's exit and bottom plate in the isothermal self-excited oscillating jet.

Denisikhina et al. [10] indicated that oscillation's amplitude-frequency characteristics in a self-excited oscillatory jet could predict accurately by applying the large eddy simulation (LES) and three-dimensional unsteady Reynolds averaged Navier-Stokes (URANS) methods. Mataoui and Schiestel [6] investigated the effects of the cavity's aspect ratio on the jet flow regime. They showed that oscillation frequency is decreased moderately with cavity height. Also, frequency is independent of the length of the cavity when impingement distance exceeds a certain value. Righolt et al. [11] developed a zero-dimensional model of the delay differential equation type for quantitatively describing

the self-sustained oscillation of a confined jet. Iachachene et al. [12] numerically investigated the effects of convection heat transfer on a slot oscillating impinging jet. They presented a relation for calculating Nusselt number with Reynolds number and geometrical parameters. Mosavati et al. [13] numerically simulated vortex ring deformation of round and square self-excited jets in a confined cavity. Their results showed that nozzleś geometry shape does not affect on the side wall's impingement point and oscillation frequency. While square oscillating nozzle has a wider spread than round one, and both have a wider jet spread (40% higher) than the free jets. Carnero et al. [8] studied the self-sustained oscillations of two turbulent isothermal opposing impinging planar water jets discharging into an open cavity under crossflow. They indicated that Reynolds number of jets plays a vital role in flow motion and behavior of the switching jets.

Appling multiple nozzles is a way to improve jet performance that have many practical engineering applications [14,15]. Aminzadeh et al. [16] reported the characteristics of the oscillatory flow caused by a double-inlet jet in a rectangular cavity compared to those of a single-inlet jet. They did not considered the effects of non-isothermal conditions. Also, Aminzadeh et al. [17] numerically studied on effects of nozzle width of self-excited oscillating impinging jets in a heated cavity at a fixed flow rate. The results indicated that Nusselt number at the impingement wall linearly changed with oscillation frequency. In addition, the cooling performance of these jets was compared to that of conventional stationary impinging jets. Aminzadeh et al. [18] numerically investigated the buoyancy mediating effects on the performance and oscillating behavior of horizontal and vertical self-excited jets under different thermal boundary conditions of the end cavity's wall (heated, cooled, and adiabatic). The results showed that non-isothermal conditions did not significantly affect the oscillating behavior of horizontal jets contrary to vertical jets. Also, Aminzadeh et al. [19] investigated the effects of limited temperatue differences in a horizontal self-excited jet with a fixed inlet velocity.

Buoyancy and momentum are forces that impact the flow field of the jet under non-isothermal conditions. According to the previous studies of Aminzadeh et al. [18,19], the significant effect of non-isothermal conditions on a self-excited oscillating jet occurs when the jet is positioned vertically. In the vertical position relative to gravity, the buoyancy force is parallel to momentum force and can affect the oscillatory behavior of the self-excited jet. Also, the interaction between buoyancy and momentum basically depends on the amount of flow rate and temperature difference. In industrial applications, these jets experience different flow rates and thermal conditions. However, the effects of different inlet flow rates at various temperatures of the

cavity's wall were not investigated yet. So, the present study was designed to simulate the vertical self-excited oscillating jet with different inlet flow rates and cavity wall temperatures. A parametric study was done on the effects of inlet Reynolds number of a plane jet issuing into a hot cavity on the flow and thermal fields.

2. METHODS

2. 1. Description of Setup   This paper studied the self-excited jet in a vertical cavity, as depicted in Figure 1. This cavity has dimensions $L \times W$. A downward oriented plane jet of thickness e is inserted centrally to a depth l, which injects the airflow with Reynolds number Re_0 and temperature of T_0 into the cavity with uniform temperature T_c. The flow can exit from two openings located above the cavity. All geometric and flow parameters are presented in Table 1.

2. 2. Numerical Models   The unsteady Reynolds averaged Navier–Stokes equations (URANS) for turbulent incompressible flow in a two-dimensional domain must be solved to simulate the present work. This purpose was carried out by the finite-volume based tool OpenFOAM code, using the Buoyant Boussinesq Pimple Foam solver enclosed by the SST k-ω turbulence model. These governing equations can be presented as follows:

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0 \tag{1}$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x} + \nu_{\text{eff}}\left(\frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial y} + \nu_{\text{eff}}\left(\frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2}\right) + g\beta(\bar{T} - T_0) \tag{3}$$
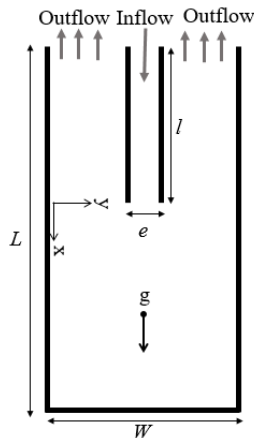
$$\frac{\partial \bar{T}}{\partial t} + \bar{u}\frac{\partial \bar{T}}{\partial x} + \bar{v}\frac{\partial \bar{T}}{\partial y} = \alpha_{\text{eff}}\left(\frac{\partial^2 \bar{T}}{\partial x^2} + \frac{\partial^2 \bar{T}}{\partial y^2}\right) \tag{4}$$

where $\bar{u}$ and $\bar{v}$ are mean velocity components, ρ denotes fluid density. ν_{eff} is effective viscosity and α_{eff} is effective thermal diffusivity. Mean temperature and static pressure are defined by $\bar{T}$ and $\bar{P}$, respectively. Also, β is the thermal expansion coefficient. Air was assumed as a Newtonian fluid with $\nu = 15.68 \times 10^{-6}$ m^2/s and $\beta = 0.0033$ 1/K. At each time interval, the time step was checked out due to maintaining the Courant number ($Co = u\Delta t/\Delta x$) below 1. Constant values of temperature (T_0) and velocity (U_0) were imposed on the inlet boundary conditions. For all walls of jet and cavity, no-slip conditions and wall functions were applied. The jet walls temperature was considered to be equal to T_0. Three values of 0, 100, and 300 were considered for the temperature difference between cavity's walls and inlet flow ($\Delta T = T_c - T_0$). Therefore, T_c accepts values 300, 400, and 600 K. The outflow condition was considered at outlet boundaries for all variables except static pressure, which was set zero.

2. 3. Mesh Study of the Computational Domain Structured and non-uniform grids were generated with a refinement around walls and near jet's exit to capture high gradients in the flow field. Several grids (20350, 23400, 26650, 30100, and 33000) were tested to ensure the grid independence of results and finally, a grid with 26650 cells was chosen as a sufficient grid resolution demonstrated in Figure 2.

2. 4. Validation of the Numerical Method   In order to validate the present numerical method, the experimental data of Mataoui et al. [9] and numerical results of Iachachene et al. [12] were used. Mataoui et al. [9] carried out an experiment on a self-excited jet discharged into a cavity at Reynolds numbers of 1300, 2600, and 4000 under isothermal conditions ($\Delta T = 0$). Measurements equipment and materials are represented in Table 2. They measured the frequency of jet oscillations. In the present work, the point with coordinates (25, 10cm) were utilized to calculate the oscillation frequency. The comparison between the

Figure 1. Studied configuration of a self-excited oscillating jet in a confined cavity

TABLE 1. Summary of simulation conditions

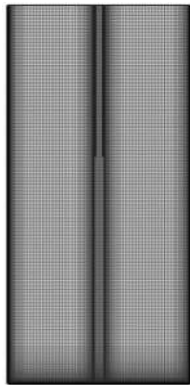|	
L (cm)	50
W (cm)	20
e (cm)	1
l (cm)	20
T_0 (K)	300
$\Delta T = T_c - T_0$	0, 100, 300
$Re_0 = U_0 e/\nu$	1000, 3000

**Figure 2.** The grid arrangement of computational domain

current simulation and experimental results [9] is shown in Table 3. A good agreement between the present results and experimental data reported by Mataoui et al. [9] can be observed in Table 3. For the second validation step, a non-isothermal case with $\Delta T = 60$ K was investigated. The non-dimensional velocity components, temperature, and pressure for the specified points with coordinates of (x/e, y/e) ((16, 4), (16, 8), (16, 16) and (8, 4) cm, respectively) were extracted from the current numerical simulation and compared with the study by Iachachene et al. [12] in Figure 3. In this study , a jet with $Re_0 = 8500$ and a temperature of $T_0=300$K was discharged into a rectangular cavity with a constant temperature of $T_c=360$ K. These comparisons confirmed that the current numerical method is feasible and valid.

TABLE 2. Measurements equipment and materials [9]

Target	Equipment	Discription
air supply	Wind tunnel	-
Velocity measurement	Hot wire anemometry	5 μm diameter platinum-plated tungsten wire
Flow visualisation	White smoke generator	composed of droplets of vegetable oil mixed in carbon dioxide
	Camera	Shooting rate of two pictures per second

TABLE 3. The computed oscillation frequency of the present study and experiment done by Mataoui et al. [9]
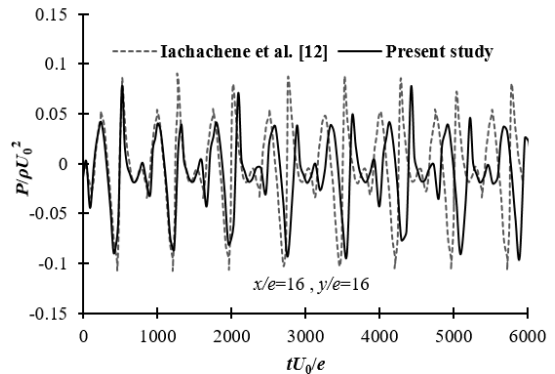
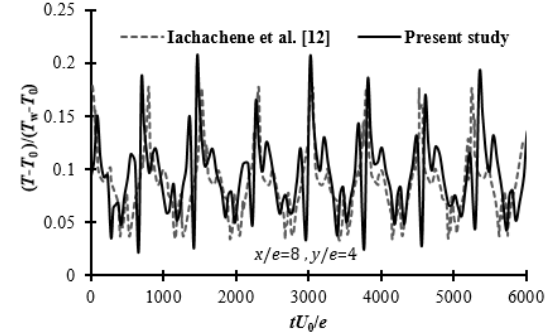|	*Re*	4000	2600	1300
***f* (Hz)**	Present study	0.63	0.39	0.19
	Mataoui et al. [9]	0.62	0.40	0.20
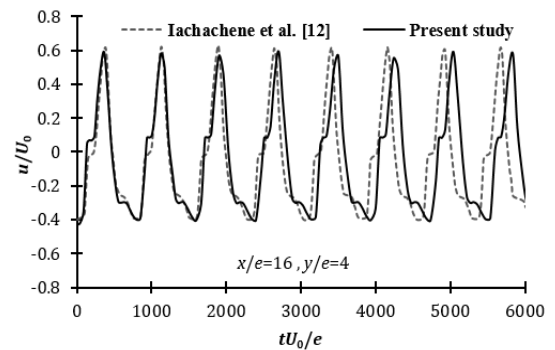
(a)
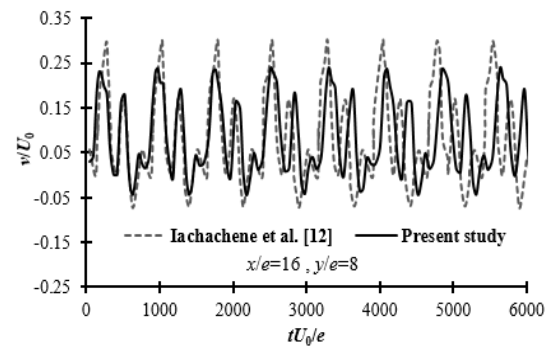
(b)

(c)

(d)

Figure 3. Comparison of dimensionless time evolution of (a) and (b) mean velocity components, (c) temperature and (d) pressure at $Re_0 = 8500$ and $\Delta T=60$ K between the present study and results reported by Iachachene et al. [12]
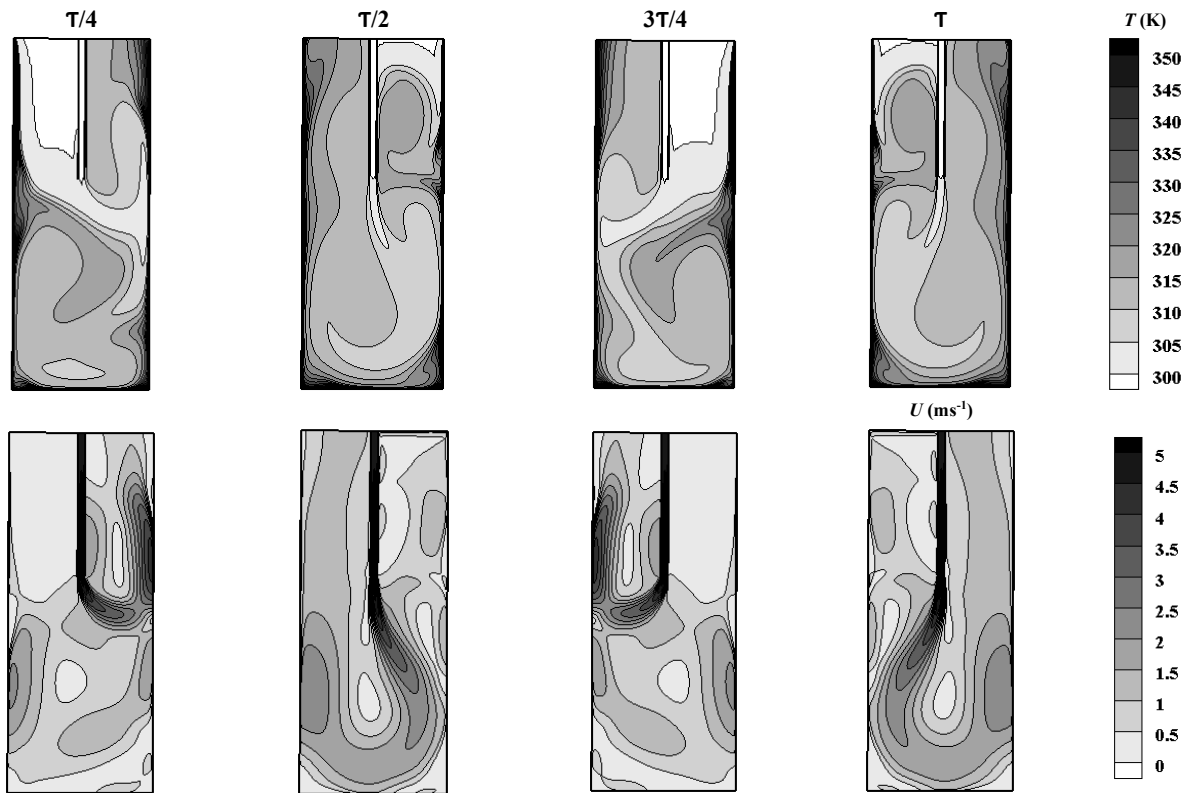
Figure 4. Temperature and velocity magnitude contours within one period of time (T=1.61 s) for *Re*=3000 and Δ*T*=100 K
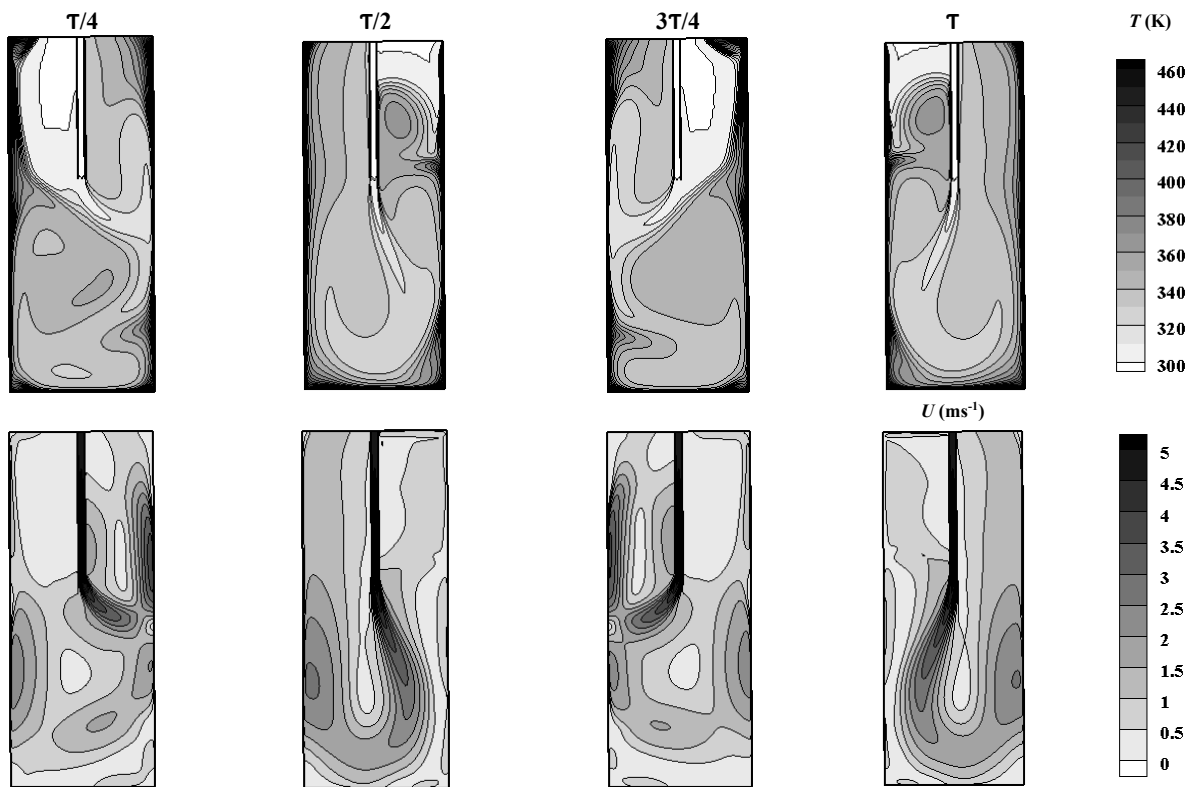

Figure 5. Temperature and velocity magnitude contours within one period of time (T=1.54 s) for *Re*=3000 and Δ*T*=300 K

3. RESULTS AND DISCUSSIONS

The self-excited jets produce an oscillatory flow that its oscillation frequency depends on the inlet velocity, geometric parameters, and thermal conditions [6, 17]. Several studies have been done on the influence of geometric parameters. In this study, the effect of inlet Reynolds number and cavity's wall temperature were studied on flow and thermal fields and oscillation characteristics of the self-excited jet. For this purpose, six cases were simulated, as depicted in Table 1.

Figures 4 and 5 show contours of temperature and velocity magnitude at four stages during one period of time for Re=3000 and temperature differences of 100 and 300, respectively. It should be noted that τ denotes oscillation period and each contour was provided after every quarter of the period. These figures illustrate the jet's flapping motions that oscillate right and left sides periodically. A comparison of Figures 4 and 5 reveals that increasing temperature differences from 100 to 300 K can almost increase the velocity magnitude in the cavity. In the vertically downward cavity, when the cold jet is discharged into the hot cavity, the momentum force and buoyancy force act in the same direction toward the bottom of the cavity. So, for Re=3000, increasing the temperature difference can raise velocity magnitude to some extent. This result is evidenced in Figure 6.

Figure 6 allows us to describe the time evolution of velocity magnitude at a specific point near the bottom wall of the cavity with coordinates (25, 10 cm) for all studied cases. As shown in Figure 6 (b), the temperature differences between the cavity's walls and inlet flow at Re=3000 can change the maximum velocity magnitude between 6 and 15% relative to the isothermal conditions. On average, for Re=1000, the temperature differences also increase the velocity magnitude. Interestingly, for Re=1000, the oscillation amplitude decreases with increasing the temperature difference until at ΔT=300 K, the jet stops flapping.

Figure 7 represents the temperature distribution over time for the specific point coordinates (25 10 cm) at each
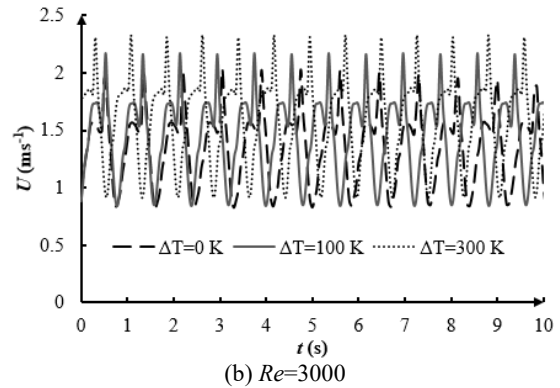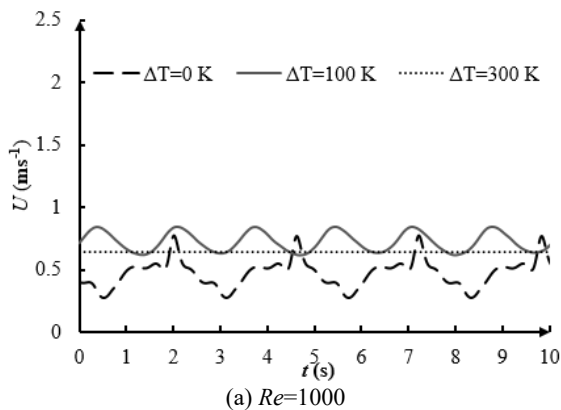
(b) Re=3000

Figure 6. Time signal of the velocity magnitude in three temperature differences for Re: (a) 1000 and (b) 3000 at the location of x=25 and y=10 cm
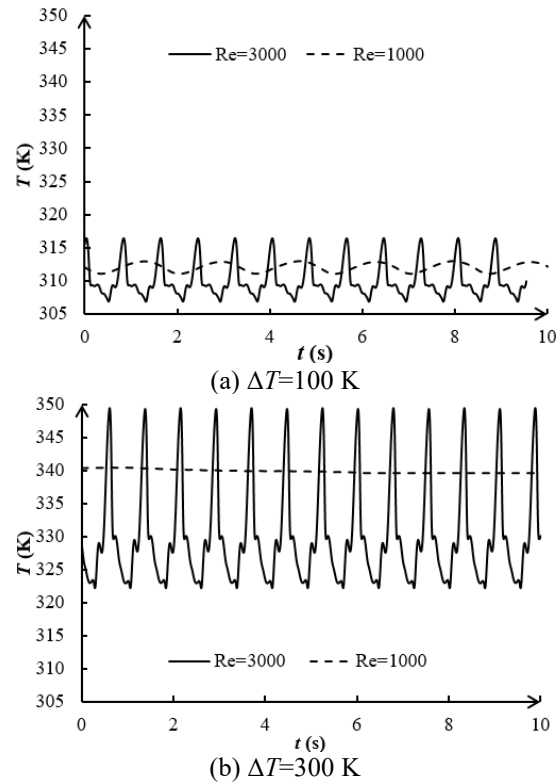
(a) ΔT=100 K

(b) ΔT=300 K

Figure 7. Time signal of the temperature in two Reynolds numbers for ΔT: (a) 100 K and (b) 300 K at the location of x=25 and y=10 cm

temperature difference. In ΔT=300 K, the amplitude of temperature oscillations for Re=3000 is enlarged nine times compared to Re=1000.

To investigate the oscillation frequency of self-excited jets, fast Fourier transform (FFT) was used. In this method, data of the specific point with coordinates (25, 10 cm) in the computational domain was extracted and applied as the input of FFT code, so the outputs are

(a) Re=1000

the frequencies. The maximum value of Fourier modes accurately determines the fundamental frequency [12]. As a sample, the output of FFT method is shown in Figure 8. The oscillation frequencies are extracted by the FFT method for all cases and reported in Table 4.

It can be deduced from Table 4 that for Re=3000, temperature differences can intensify the frequency by up to 10% in comparison with the isothermal self-excited jet. It is interesting to note that for Re=3000 the oscillation frequency slightly changes despite the temperature differences. This phenomenon is almost certainly due to the interaction between momentum and buoyancy forces. This interaction can be assessed by calculation of Archimedes number (Ar).

Ar is defined by the buoyancy to momentum ratio as $Ar = g\beta W\Delta T/U_0^2$ [20]. The results obtained from Ar calculations are presented in Table 4. At Re=3000, values of Ar are below 0.1 for both temperature differences of 100 and 300 K. It means that the role of buoyancy force, against momentum force is negligible in the flow field. Therefore, at Re=3000, changing cavity's thermal boundary conditions has little effect on the oscillation characteristics, i.e., the frequency and amplitude of oscillations.

As Table 4 shows, there is a significant difference in the frequency values between ΔT=100 K and isothermal conditions at Re=1000. As observed in Figures 6 and 7, in conditions of Re=1000 and ΔT=300 K, the flow has no oscillation motion. Indeed, for Re=1000 that has a weaker momentum force than Re=3000, values of Ar are larger than 0.1. Hence, buoyancy as well as temperature

difference, can play a key role in the behavior of self-excited jet. That's why changing ΔT from 0 to 100 can raise the oscillation frequency about 58%. But more increasing of ΔT to 300 K enlarges Archimedes number more than 0.7 and non-oscillatory flow was observed.

From a physical point of view, it can be said that the heated cavity's walls can strengthen the buoyancy mechanism and the tendency of the air inside the cavity to escape through the upper outlets increases. As a result, the pressure decreases locally due to the relative increase in air velocity adjacent to the lateral walls of the cavity. This can amplify the Coanda effect [6, 9] (oscillating behavior due to the drop in periodic pressures in the side walls) and increase the jet oscillation frequency. As can be seen in Table 4, at Re =3000, the frequency of jet oscillations increases as the cavity heats up. The same behavior is observed to some extent at Re =1000. Thus, at Re =1000, by providing the temperature difference of 100 K between the cavity walls and the jet, the frequency of jet oscillations increases from 0.19 (in the isothermal state) to 0.3. However, by raising the temperature difference to 300 K, an increase in the trend of frequency does not continue and the jet becomes non-oscillating. As can be seen in Table 4, as the temperature difference increases to 300 K, the Archimedes number (Ar) increases to about 0.78, which means that the ratio of buoyancy force versus momentum is significant. In such a situation, the opposition of these two mechanisms can cause instability in the oscillating jet behavior and makes it non-oscillating, or sometimes cause irregular random oscillations with limited amplitude, which are usually classified in the non-oscillating category [18].

In the case of Reynolds number 3000, because Ar is very small (much less than 0.1), an increase in the temperature difference between the jet and the wall, even up to 300 K, can not cause the buoyancy and momentum mechanisms to interfere and thus change the jet oscillation regime. The earlier work [18] showed that where Ar is less than 0.1, the effects of the cavity's thermal boundary conditions on the oscillating jet's behavior are not significant. However, in cases where Ar exceeds 0.1, the buoyancy effects due to the temperature difference influence the characteristics of oscillating flow.
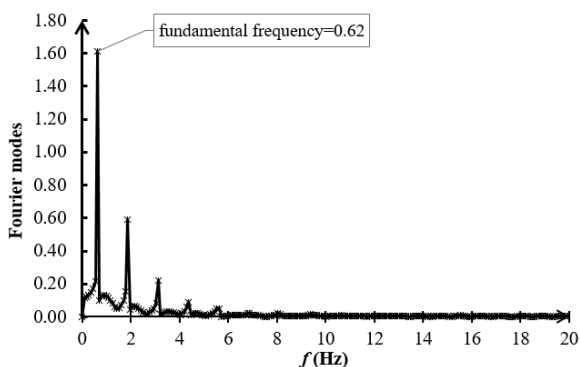

Figure 8. Typical Fourier modes time signal of the mean velocity for Re = 3000 and ΔT=100 K

TABLE 4. Oscillation frequency of the studied cases

Re	1000			3000		
ΔT (K)	0	100	300	0	100	300
f (Hz)	0.19	0.30	Non-oscillatory flow	0.59	0.62	0.65
Ar	-	0.26	0.78	-	0.03	0.09

4. CONCLUSIONS

Numerical simulations were employed to investigate the effects of inlet flow rate in various temperature differences on the behavior of self-excited oscillating jet. In the recent years, studying the self-excited jet under non-isothermal conditions has received much attention due to its wide range of industrial applications. In the previous works, the effects of various Reynolds numbers and temperature differences on the oscillatory flow were

not investigated. For this purpose, a plane jet with a fixed temperature of 300 K and Reynolds numbers (Re=1000 and 3000) discharging vertically downward into a rectangular cavity was considered. In the studied problems, the cavity's walls experienced various temperatures to create temperature differences of 0, 100, and 300 K relative to inletflow. The key conclusions are as follows:

- With capturing the time variation of velocity magnitude in the specific point located at the computational domain, it was determined that at Re=3000, the temperature differences between cavity's walls and inlet jet could affect maximum velocity magnitude between 6 and 15% relative to the isothermal conditions.

- Also, time variation of the temperature at ΔT=300 K for the specific point showed that the amplitude of temperature oscillations for Re=3000 is enlarged by about nine times compared to Re=1000.

- It is deduced from the results that in Re=3000, the temperature differences can increase oscillation frequency up to 10% compared to isothermal conditions. This value equals to 58% at Re=1000.

- The jet at Re=1000 and ΔT=300 K acts as a non-oscillatory jet due to the interaction between momentum and buoyancy forces.

- For Archimedes number (Ar) below 0.1, the frequency and amplitude of oscillations are slightly dependent on the temperature differences.

- For Re=1000 and ΔT=300 K, the flow stopped oscillating. In this case, Archimedes number was enlarged more than 0.7, which is indicative of momentum weakness in driving the oscillating flow.

- Further experimental studies are require for prefect understand and more accurately identify complex phenomena that occur in the range of relatively low Reynolds numbers and high-temperature differences that the opposition of the buoyancy and momentum mechanisms may lead to instability of the oscillating jet.

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Persian Abstract

چکیده

جت نوسانی خود-تحریک می‌تواند با تخلیه یک جت صفحه‌ای در یک حفره مستطیلی به دلیل اثرات فشار و بدون نیاز به کمک خارجی به طور طبیعی ایجاد شود. در سال‌های اخیر، جت خود-نوسانی غیر هم‌دما به دلیل کاربردهای صنعتی گسترده‌ای که دارد، مورد توجه محققین قرار گرفته است. بر این اساس، مطالعه حاضر به منظور مقایسه رفتار نوسانی جت خود-تحریک عمودی پایین‌زن با عدد رینولدز (Re) ۱۰۰۰ و ۳۰۰۰ تحت شرایط اختلاف دماهای مختلف بین جریان ورودی و دیواره‌های حفره (۰، ۱۰۰ و ۳۰۰) انجام شده است. محاسبات عددی با استفاده از معادلات گذرای ناویر-استوکس میانگین‌گیری شده به روش رینولدز (URANS) و معادله انرژی برای یک جریان تراکم‌ناپذیر به دست آمده است. شبیه‌سازی عددی توسط ابزار حجم محدود اپن‌فوم اجرا شده است. نتایج نشان داد که در حالات مورد بررسی، بسته به مقدار اختلاف دما، جریان های نوسانی و غیر نوسانی مشاهده می‌شود. همچنین در Re=۳۰۰۰ اختلاف دما می‌تواند فرکانس نوسان را تا ۱۰ درصد نسبت به شرایط هم‌دما تغییر دهد. این مقدار در Re=۱۰۰۰ به ۵۸٪ می‌رسد. نتایج نشان داد در حالتی که عدد ارشمیدس کمتر از ۰.۱ است، تأثیر اختلاف دمای جت و دیواره حفره بر رفتار نوسانی ناچیز می‌باشد.