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# Numerical investigation on the fluid flow and heat transfer of non-Newtonian multiple impinging jets

R. Gharraei [a,*], A. Vejdani [a], S. Baheri [b], A.A. Davani D. [c]

[a] *Mechanical Engineering Department, Azarbaijan Shahid Madani University, Iran*
[b] *Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran*
[c] *Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA, United States*

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ABSTRACT

Laminar power-law non-Newtonian fluid flow and heat transfer characteristics of multiple impinging square jets have been studied, numerically. The effect of inlet Reynolds number, jet-to-plate spacing and fluid power-law index on the flow structure and wall Nusselt number has been investigated. Numerical results have been presented for Reynolds numbers 100, 200, power-law indices 0.4–1.6 and dimensionless jet-to-plate spacings 0.25–1.0. Results showed that for a given Reynolds number and consistency coefficient, increasing of the power-law index leads to the higher impingement velocity and higher wall Nusselt number. For higher jet-to-plate spacings, the peripheral entrainment vortices are created around the jet body and by decreasing the spacing, these vortices disappear. Furthermore, the numerical results showed that decreasing of jet-to-plate spacing increases the wall Nusselt number.


## 1. Introduction

Impinging jets are used in many industrial and engineering applications such as rapid cooling/heating, paper and textile drying, tempering of glass and cooling of electronic components. There are many experimental and numerical studies on the flow field and heat transfer behavior of impinging slot jets in literature [1–5]. Aldabbagh and Mohammad [6] studied the flow and heat transfer characteristics of a laminar square jet impingement on a flat plate in different jet-to-plate spacings; their results showed the Nusselt number has four peaks at the four corners of the jet cross section and the heat transfer increases as jet-to-plate spacing decreases. Chatterjee [7] studied flow characteristics of axisymmetric impinging jet numerically. The results showed that for small jet-to-plate spacings, regardless of Reynolds number, vorticity generated at the downstream of impinging jet diffuses upstream and changes the velocity distribution in the exit plane of jet. In the other study on the same geometry, Chatterjee and Daviprasath [8] denoted that flow development in the upstream of jet is responsible for off-stagnation maxima points, which occurred in Nusselt number distribution on the impinging plane. Chatterjee [9] studied evolution of flow structure and multiple vortex formation for single axisymmetric impinging jet of Newtonian fluid. Numerical results showed the progressive formation of vortices due to multiple separation and reattachments occurred in the downstream of impingement point. At a given Re number, in addition to primary and secondary vortices placed on confining and impinging plates, the tritary vortex can be formed for specific range of jet-to-plate spacings.

The jets discharge from single round or rectangular nozzles have a localized high heat transfer rate but multiple jets produce a more uniform cooling or heating. Aldabbagh and Sezai [10,11] studied the flow structure and heat transfer characteristics of twin jets and multiple jets impingement, numerically. Their results indicated a peripheral vortex around each jet. Size and location of peripheral vortices depends on the jet-to-plate spacing.

Zhao et al. [12] studied the heat transfer of impinging jet cluster with four different nozzle shapes: circular, square, rectangular and elliptic. Considering the average Nusselt number, they concluded that for small jet-to-plate spacing and Re number, rectangular jet cluster has the best performance and circular cluster offers the lowest Nusselt number. They showed that, although the heat transfer performance in the central region for a single jet is higher than that for the cluster of same shape jets but cluster can provide a relatively uniform local Nusselt number.

* Corresponding author. Mechanical Engineering Department, Azarbaijan Shahid Madani University, Tabriz, Iran. Tel.: +98 41 34327566.
*E-mail address:* gharraei@azaruniv.ac.ir (R. Gharraei).

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**Nomenclature**

| | |
|---|---|
| $A_z$ | $L_z$/B aspect ratio |
| B | jet width |
| h | heat transfer coefficient |
| $L_x$, $L_z$, $L_y$ | length of domain in x, y and z directions respectively |
| k | thermal conductivity |
| m | consistency factor |
| n | power-law index |
| Nu | Nusselt number |
| P | pressure |
| $q''$ | local convective heat flux in impingement wall |
| Re | Reynolds number |
| u, v, w | Cartesian velocity components |
| U, V, W | non-dimensional velocity components (normalized by $W_{in}$) |
| x, y, z | Cartesian coordinates |
| X, Y, Z | non-dimensional Cartesian coordinates |
| $X_n$,$Y_n$ | spacing of jets in x and y directions respectively |
| $\vec{V}$ | velocity vector |
| T | temperature |

*Subscripts*

| | |
|---|---|
| in | jet inlet |
| w | impingement wall |
| in_1 | jet inlet for Newtonian fluid |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density |
| $\eta$ | effective viscosity |
| $\dot{\gamma}$ | strain rate |
| $\bar{\bar{\sigma}}$ | stress tensor |
| $\bar{\bar{I}}$ | unit tensor |
| $\bar{\bar{\tau}}$ | deviatoric stress tensor |
| $\bar{\bar{\dot{\gamma}}}$ | strain rate tensor |

Although non-Newtonian fluids are encountered in various applications such as food, medicine and chemical industries, there are few studies on the non-Newtonian impinging jets. Gorla [13] used the similarity solution for the study of impingement of laminar swirling power-law fluid jet normally on a horizontal plane with a free surface. Similarity solution for a region away from the central stagnation point could predict the radial and swirling velocities for the flow of non Newtonian fluids. Poh et al. [14] studied numerically the heat transfer characteristics of a single axisymmetric laminar jet impingement normally on a plane wall for several carboxymethyl cellulose (CMC) aqueous solutions, which behave as the power-law fluids. The effect of the jet Reynolds number, jet exit velocity and jet-to-plate spacing on the heat transfer rate were studies. It was found that at a fixed Reynolds number, the fluids with lower power-law index have higher wall Nusselt number due to higher jet exit velocity. The heat transfer characteristics of a purely viscous inelastic non-Newtonian fluid discharged from a confined laminar axisymmetric jet were studied by Chatterjee et al. [15], using the Carreau viscosity model. The effects of the dimensionless jet-to-plate spacing, rheological parameters as well as Reynolds and Prandtl numbers on the magnitude of the off-stagnation point peak heat transfer rate were reported. Arzate and Taguy [16] studied the hydrodynamic of liquid impinging jet in high-speed jet coating for Newtonian and shear-thinning fluids. They used the flow visualization for identification of stable coating condition. The experimental results showed that Newtonian jets have a straight trajectory for all speeds of moving web but the stream of shear-thinning jets is curved-shape. Cavadas et al. [17] studied the flow field created by impingement of a non-Newtonian laminar slot jet on a flat plate confined by sloping walls. Their experimental and numerical studies indicated the presence of a recirculating zone attached to sloping walls which its size increases with Reynolds number. A three-dimensional effect was found inside the test cell, which was characterized by a wall jet near the side walls and the concomitant absence of a separated flow region there. Chatterjee [18] studied impingement of axisymmetric single jet of inelastic Carreau fluid and analyzed the effect of fluid rheology on Nusselt number distribution on impinging surface. Substantial augmentation of heat transfer occurred both in the impinging and wall jet regions. In the wall jet region, the primary vortex was responsible for heat transfer enhancement. The size and length of primary separation vortex were increased as viscosity dependence on strain rate became steeper. The larger vortices could maintain a thin thermal boundary layer along the impinging wall and lead to higher Nusselt numbers.

It is clear from a careful survey of the literature that in spite of the large body of work on confined single and multiple Newtonian impinging jets, there is a lack of study about impingement of non-Newtonian multiple jets on a plate. Considering the importance of non-Newtonian fluids in various industries, the power-law non-Newtonian fluid flow and heat transfer behavior of multiple impinging jets have been studied, numerically in this study. The effect of various parameters such as inlet jet Reynolds number, power-law index of the fluid and jet-to-plate spacing (lower than one jet width) on the flow and heat transfer of impinging streams have been investigated. Also, the behavior of non-Newtonian impinging jets has been compared with the Newtonian ones.

## 2. Mathematical model and numerical solution

Fig. 1, shows the geometrical characteristics of the computational domain. Five square jets issue from upper plane of channel and impinge normally to the lower wall.

Dimensions of domain can be described by $L_x = L_y = 35\,B$ and $X_n = Y_n = 5B$, which B is the width of the jet. Considering the steady laminar flow of an incompressible non-Newtonian power-law fluid,

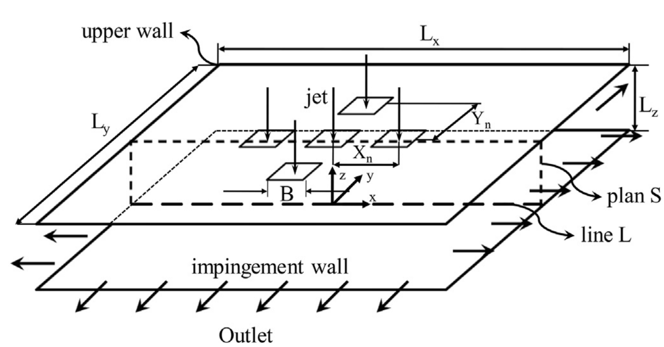


**Fig. 1.** Geometrical characteristics of computational domain.