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# Numerical investigation of thermal mixing of shear thinning fluids in one-way opposing jets

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## Abstract

In recent years, impinging streams have received increasing interest for their high efficiency in heat and mass transfer. This numerical study was conducted to investigate flow and heat transfer characteristics of one-way opposing jets of non-Newtonian fluids. Effects of Reynolds number impinging angle, momentum ratio and flow behavior index on mixing index were evaluated. The results showed improvement of thermal mixing due to an increase in Reynolds number, flow behavior index and momentum ratio in impinging zone. This study also demonstrated that thermal mixing along the channel increased as the Reynolds number and momentum ratio decreased. Nevertheless, augmentation of the flow behavior index resulted in higher thermal mixing along the channel. The impinging angle had no significant effect on thermal mixing along the channel; but, with increasing impinging angle, thermal mixing improved in the impinging zone.

## Nomenclature

| | | | |
|---|---|---|---|
| $C_p$ | *specific heat, [J/(kg.K)]* | $U$ | *velocity in x direction, [m/s]* |
| $D$ | *diameter of inlet jets, [m]* | $V$ | *velocity in y direction, [m/s]* |
| $H$ | *channel height, [m]* | $X, Y$ | *dimensional coordinates , [m]* |
| $K$ | *thermal conductivity, [W/(m.K)]* | **Greek symbols** | |
| $m$ | *consistency index of power-law fluid, [Pa.s]* | $\dot{\gamma}$ | *shear rate, [1/s]* |
| $MI$ | *mixing index* | $\rho$ | *density of fluid, [Kg/m3]* |
| $n$ | *flow behavior index* | $\sigma$ | *standard deviation of temperature, [K]* |
| $Pa$ | *pressure,[Pa]* | $\tau$ | *stress, [Pa]* |
| $T$ | *temperature of fluid, [K]* | **Subscript** | |
| $\Delta T$ | *temperature difference, [K]* | $j$ | *jet inlet* |

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## 1. Introduction

Opposing jets have attracted great research efforts in two recent decades because of the need for achieving rapid and uniform mixing of two or more gas/ liquid streams in a number of industrial and food applications without mechanical assistance. As a result of collision of the opposed jets, a narrow zone, which offers excellent conditions for transport processes, is created. The stream then leaves the system through the exits symmetrically situated on either side of the impingement region. Due to their high efficiency of mixing and good characteristics of flow and thermal fields, impinging streams reactors (ISRs) have found many applications in chemical and food industries. A number of publications have reportede different applications of impinging streams [1–8]. Although a number of experimental works have been performed for different applications of opposing jets, there are still few fundamental studies on heat and/or mass transfer of opposing jets. The laminar flow regime of ISR is important when dealing with high viscosity flows; e.g. polymer solutions, polymer melts, liquid food stuffs, etc.

Roy et al. [9] considered laminar opposing jets in a two-dimensional junction flow (one way opposing jets) both theoretically and experimentally. They studied effects of flow and geometric parameters on velocity and thermal fields for both forced and mixed convection cases and found reasonably good agreement between theoretical and experimental results for both forced and mixed convection regimes. Hosseinalipour and Mujumdar [10, 11] developed the first numerical model for two confined plane opposing jets with isothermal boundaries and adiabatic walls in steady laminar as well as turbulent flows, respectively. An extensive parametric study was carried out to study geometric and hydrodynamic effects on flow and heat transfer characteristics along with effects of equal and unequal opposing jets on them. Temperature at the cross- section was used as a passive tracer to evaluate mixing flow characteristics. They also studied drying of particles in an opposing jet dryer using the Lagrangian modeling approach [12]. Devahastin and Mujumdar [13] investigated flow and mixing characteristics of two-dimensional laminar confined impinging streams. The time-dependent solution of conservation equations for mass, momentum and energy was carried out in order to find Reynolds numbers, beyond which the flow became oscillatory. They found that both inlet jet Reynolds number and the system geometry had strong effects on mixing in impinging streams. It was claimed that these results could be used as a preliminary design tool for in-line mixer design for high viscosity fluids. Very few researchers have studied thermal and flow characteristics of non-Newtonian impinging streams or impinging jet. However, non-Newtonian impinging streams have many applications in food and chemical industries. Poh et al. [14] studied flow and heat transfer characteristics of a single axis-symmetric semi-confined laminar jet impinging normally on a plane wall for a purely viscous power law fluid. Effects of Reynolds number, jet exiting velocity and distance between nozzle and plane were also considered. According to their results, at a fixed Reynolds number for power law fluids, decrease of power index would increase magnitude of Nusselt number. Heat transfer characteristics of a purely viscous inelastic non-Newtonian fluid discharged from a confined laminar asymmetric jet were studied by Chatterjee et al. [15] while assuming the Carreau viscosity model. Important features of non-Newtonian developing flow field were described and compared with those of its Newtonian counterpart. Effects of the dimensionless nozzle-to-plate distance, rheological parameters as well as Reynolds and Prandtl numbers on the magnitude of the off-stagnation point peak heat transfer rate were also reported. Devahastin and Srisamran [16] considered numerical simulation of flow and mixing characteristics of laminar impinging streams of shear-thinning fluids and investigated effects of various parameters (i.e. jet Reynolds number and flow behavior index) on flow and mixing characteristics and reported that, when

Reynolds number of jets increased, the jet interaction in impinging zone and size of recirculation zone increased. Cavadas et al. [17] investigated influences of shear-thinning intensity and Reynolds number on steady flow of power law fluids within an impinging jet cell. They studied pressure loss and size and strength of recirculation region formed along the sloping surfaces of the cell and reported that size and strength of the recirculation zone increased with increasing the Reynolds number. Adane and Tachie [18] studied three-dimensional laminar wall jet flows of shear-thinning non-Newtonian fluids using a particle image velocimetry (PIV) technique. The velocity was calculated in various streamwise-transverse and streamwise-spanwise planes for various jet Reynolds numbers. According to their measurements, maximum velocity decay, jet half-width and velocity profiles were obtained to study effects of Reynolds number and fluid type on characteristics of the wall jet flows. They observed that maximum velocity decay and jet half-width depended on inlet Reynolds number and fluid type.

In the present numerical study, thermal mixing was considered in one-way opposing streams in impinging zone and along the channel for shear thinning fluid and effects of various hydrodynamic and geometry parameters were thoroughly investigated and discussed.

## 2. Mathmatical fundamental

### *2.1. Geometry configuration*

A schematic diagram of one-way opposing jets configuration is shown in Fig. 1. One-way opposing jets configurations include two fluid streams of different temperatures which are injected into the system through the two closed inlets. These two streams can be entered into the system with variable impinging angle. The impinging zone, i.e. 0<X<0.8, is illustrated in Fig. 1. In this region, diffusion phenomenon is remarkable. The studied impinging angle (α), defined as the angle between jet inlet and confined walls, are α=30°, 45°, 60° and 90°. The entered streams leave the system through channel outlet.

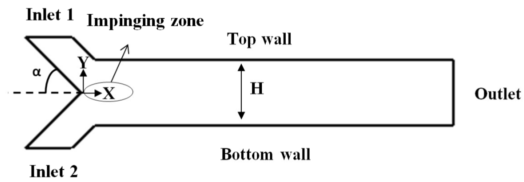



**Fig. 1.** Schematic model of one-way opposing jets.

### *2.2. Assumptions and governing equations*

In order to formulate mathematical description of flow in one-way opposing jets, the following considerations were assumed: the flow through channel was laminar, steady state, two-dimensional and incompressible, natural convection and thermal radiation were neglected and properties of the fluid were constant. Under such conditions, the general governing equations can be written as follows:

Conservation of mass:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

Conservation of momentum in x direction:

$$\rho(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y})=-\frac{\partial P}{\partial x}-[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial_{yx}}{\partial y}] \qquad (2)$$

Conservation of momentum in y direction:

$$\rho(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y})=-\frac{\partial P}{\partial y}-[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial_{yy}}{\partial y}] \qquad (3)$$

Conservation of energy:

$$\rho C_p(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y})=k[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}] \qquad (4)$$

where shear stress of shear-thinning fluids is formulated by:

$$\tau=\left\{m\left|\sqrt{\frac{1}{2}(\dot{\gamma}:\dot{\gamma})}\right|^{n-1}\right\}\dot{\gamma} \qquad (5)$$

where $n$ is flow behavior index, $m$ is consistency index and $\dot{\gamma}$ is shear rate tensor, which is calculated by [15]:

$$\frac{1}{2}(\dot{\gamma}:\dot{\gamma}) = 2[(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2] + [\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y}]^2 \qquad (6)$$

In this study, carboxymethyl cellulose (CMC) solutions were used as shear-thinning fluids. Table 1 lists different values of flow behavior index (n) and consistency coefficient (m) at different concentrations [19]. Physical properties of CMC solutions are also listed in Table 2 [20].

**Table 1.** Flow parameters of CMC solutions [19].

| Concentration of CMC(ppm) | n | m |
|---|---|---|
| 100 | 0.9512 | 0.00383 |
| 500 | 0.8229 | 0.00849 |
| 2000 | 0.7051 | 0.02792 |

**Table 2.** Physical properties of CMC solutions used in this study [20].

| Property | Value |
|---|---|
| Density ($\rho$) | 1000 kg. $m^{-3}$ |
| Specific heat ( $C_p$ ) | 4100 $J.kg^{-1}.K^{-1}$ |
| Thermal conductivity (k) | 0.7 $W.m^{-1}.K^{-1}$ |

### *2.3. Reynolds number and mixing index*

One of the most important factors that may affect mixing behavior of two streams is Reynolds number. For non-Newtonian flow, Reynolds number based on the width of the inlet jet is defined as:

$$Re = \frac{(D^n v_j^{2n-1}\rho)}{(8^{n-1}m)}(\frac{4n}{3n+1})^n \qquad (7)$$

where D is width of inlet jet and $v_j$ is its velocity. Another studied parameter was mixing index (MI). Temperature at the cross-section was used as a passive tracer to evaluate mixing flow characteristics. The mixing index was defined as follows:

$$MI = \frac{\sigma_T}{\Delta T} \qquad (8)$$

where $\sigma_T$ is standard deviation of the fluid temperature across the channel height in any determined axial location and $\Delta T$ is temperature difference of the two inlet streams. A well-mixed condition is represented by $\sigma_T = 0$.

## 3. Numerical simulation

### *3.1. Solution procedure*

Conservation equations, along with boundary conditions, were solved using finite element method-based commercial software Ansys, version 5.4 [21]. Element Flotran 141 was used to solve the present two-dimensional CFD problem. The descritized momentum and temperature equations were solved using well-known TDMA technique which was provided as a solution approach for discretized equations in the commercial software. Also, the SIMPLEN algorithm was adopted for resolving the pressure-velocity coupling system.

T The solution converge was met when the normalized residuals for all the equations reached $10^{-6}$. Readers can find more details about the solution procedure in [21].

### *3.2. Boundary conditions*

In the present simulation, the following boundary conditions were used: a flat velocity and temperature profile was applied at the inlets, temperature difference of two opposing jets was kept 10°C, all walls were considered to be adiabatic and no-slip conditions were imposed on them and the fully developed boundary condition was applied at the outlet.

*3.3. Mesh independency test*

In this study, many cases were studied. So, it was not possible to check grid independence for each individual case. To overcome this problem, as suggested by Hosseinalipour and Mujumdar [10], the appropriate number of grids was found using a grid doubling procedure for the "worst" case with the highest Reynolds number for each geometry and applied to all other cases for that particular geometry. Figure 2 shows effect of grid size on the predicted axial velocity. Typically, grid density of 200 × 1200 provides mesh independency solution of the problem.

## 4. Results and discussion

*4.1. Validation of the results*

The numerical simulation was verified by comparison with two separate cases. In order to validate flow behavior, the numerical simulation was compared with the experimental results of Roy et al. [9], who studied mixing flow in a junction (one-way opposing jets). The channel height was twice more than width of inlet channels. All the walls were specified adiabatic (insulated walls). Reynolds number was equal to 500 based on mean exit velocity of channel. Figure 3 compares the numerical predicted dimensionless axial velocity profiles with the experimental results of Roy et al.

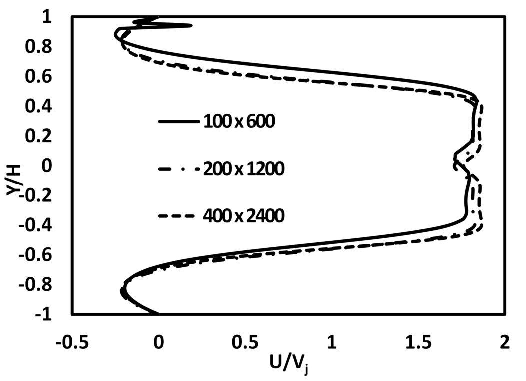



**Fig. 2.** Effect of grid density on the dimensionless velocity, Re=500, H/D=2 , n=0.8.

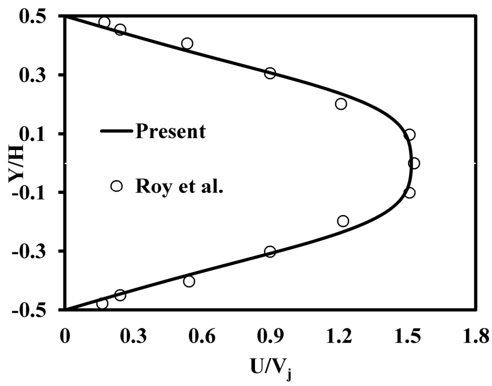



**Fig. 3.** Validation of axial velocity with experimental result, Re=500, H/D=2.

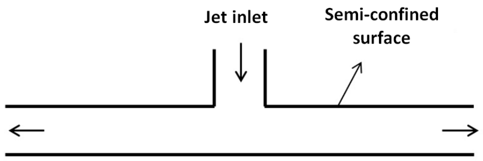
It can be seen that results of the present study were in good agreement with the experimental data.In order to validate thermal behavior, the predicted local Nusselt number was compared with numerical results of Poh et al. [14], who studied flow and heat transfer under axisymmetric laminar impinging jet of power-law fluids, as shown in Fig. 4(a).

In this study, 20°C water was issued from an opening and normally injected on a plane wall at T = 30°C. The inlet jet Reynolds number of the fluid was calculated based on the inlet jet diameter (D = 0.02 m). Also, commercial CFD software, FLUENT 6.0, was utilized to solve the governing equations. Comparison of the plots of the local Nusselt number (Eq. (9)) versus dimensionless distance using the present numerical simulation and that of Poh et al. [14] is shown in Fig. 4(b). It can be seen that simulation results of the present study had good agreement with the available experimental data.

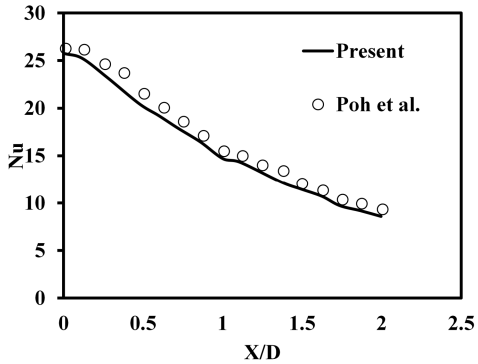
$$Nu(x) = -\frac{D}{(T_w - T_j)}\frac{\partial T}{\partial y} \tag{9}$$

*4.2. Effect of Reynolds number on mixing index*

The mixing behavior of opposing jets in impinging zone and along the exit channel was separately investigated. The behavior of mixing index near to impinging zone and along the channel was different. Fig. 5(a) shows trend of mixing index versus dimensionless axial distance (x/D) in the vicinity of impinging zone.




(a)



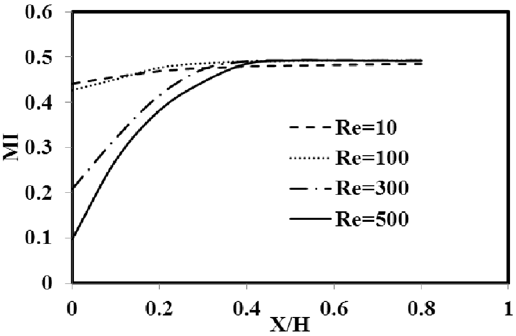

(b)

**Fig. 4**. Validation of thermal behavior (a) impinging jet configuration of Poh et al. [14] (b) Verification of predicated local Nusslet number by results of Poh et al. [14].

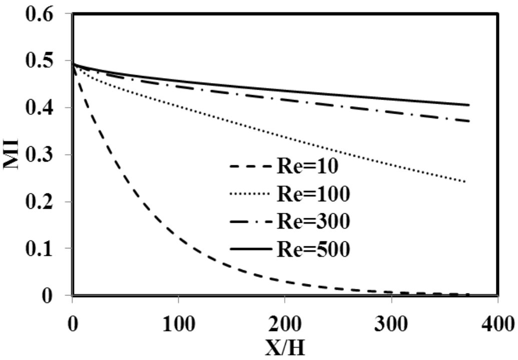
An increase of Reynolds number led to improvement in behavior of opposing jets in impinging zone due to more diffusion of jets into each other. A contradictory behavior was observed in the regions far from the impinging zone. Fig. 5(b) depicts trend of mixing index versus dimensionless axial distance (x/D) through the channel. It can be seen that thermal mixing along the channel improved as Reynolds number decreased and the best thermal mixing occurred at Re=10, which was due to this fact that an increase in Reynolds number led to less residence time of fluid particles in the laminar flow.

### *4.3. Effect of flow behavior index on mixing index*

Variations of mixing index versus dimensionless axial distance (x/D) at various flow behavior indexes (n) in the vicinity of impinging zone are shown in Fig. 6(a). In impinging zone, an increase of n led to better mixing behavior due to larger diffusion of the jets with higher n in comparison with lower one.




(a)



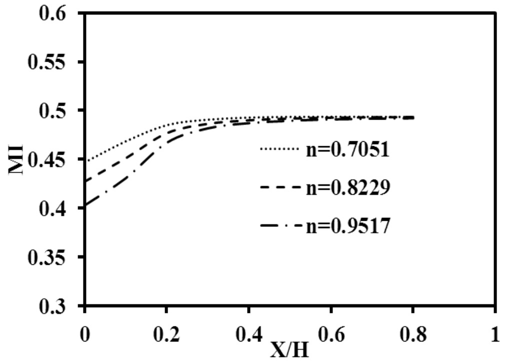

(b)

**Fig. 5.** Effect of Reynolds number on mixing index (a) in impinging zone (b) along the channel, H/D=2, n=0.8229.

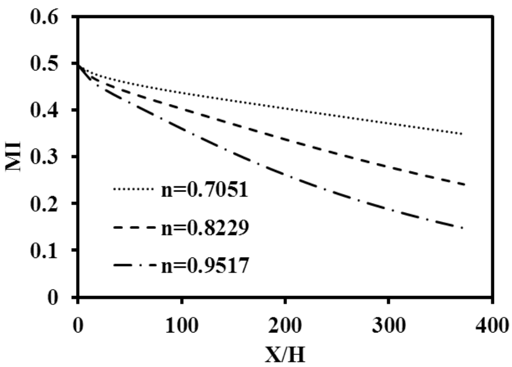
Trend of mixing index through the channel is illustrated in Fig. 6(b). An increase of flow behavior index in this zone led to improvement of mixing behavior with a shorter exit channel length for better mixing, which can be explained as follows: according to Eq. (7), inlet velocity decreased as flow behavior index increased. So, fluid particles resided more time in channel which resulted in better thermal mixing.

### *4.4. Effect of impinging angle on mixing index*

Effect of jet inlet angle is considered in this section. Fig. 7(a) shows trend of mixing index versus dimensionless axial distance (x/D) for three inlet angles (α=30°, 60° and 90°) in impinging zone. As the inlet angles increased, mixing behavior improved due to the increase of diffusion of two jets. Fig. 7(b) illustrates the mixing index behavior through the channel. As is observed, the jet inlet angles had no considerable effect on the mixing index along the channel because various inlet angles did not affect residence time of fluid particles in the same Reynolds number.




(a)



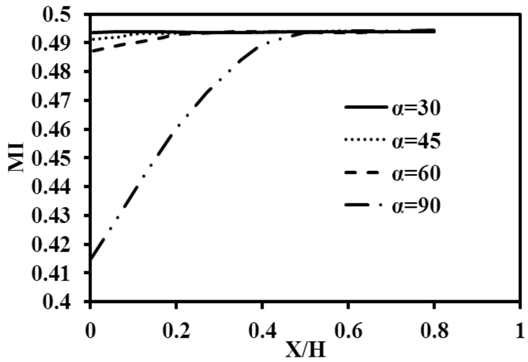

(b)

**Fig. 6.** Effect of flow behavior index on mixing index (a) in impinging zone, (b) along the channel, Re=100, H/D=2.

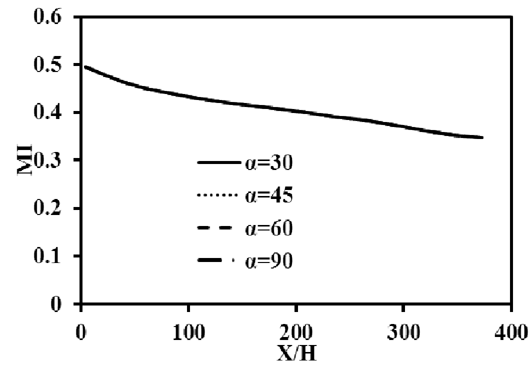
*4.5. Effect of momentum ratio on mixing index*

The effect of the two jet momentums is studied in this section. Fig. 8(a) shows the mixing index behavior versus dimensionless axial distance (x/D) for three momentum ratios (M=1, 1.5, 2) in impinging zone. Jets with unequal momentums produce stagnation plane shifted towards the weaker jet. Therefore, unequal inlet momentum led to a more instability s and better mixing in impinging zone.

The mixing index as a function of channel length is shown in Fig. 8(b).As one can see the mixing index decreases as momentum ratio decreases and the best value is detected at M=1 . This is due this fact that overall mass flow rate increases as momentum ratio increases. Therefore lower momentum ratio causes the improvement of thermal mixing along the channel due to shorter residence time of fluid particles.




(a)




(b)

**Fig. 7.** Effect of jet inlet angles on mixing index (a) in impinging zone, (b) along the channel, Re=100, H/D=2, n=0.8229.

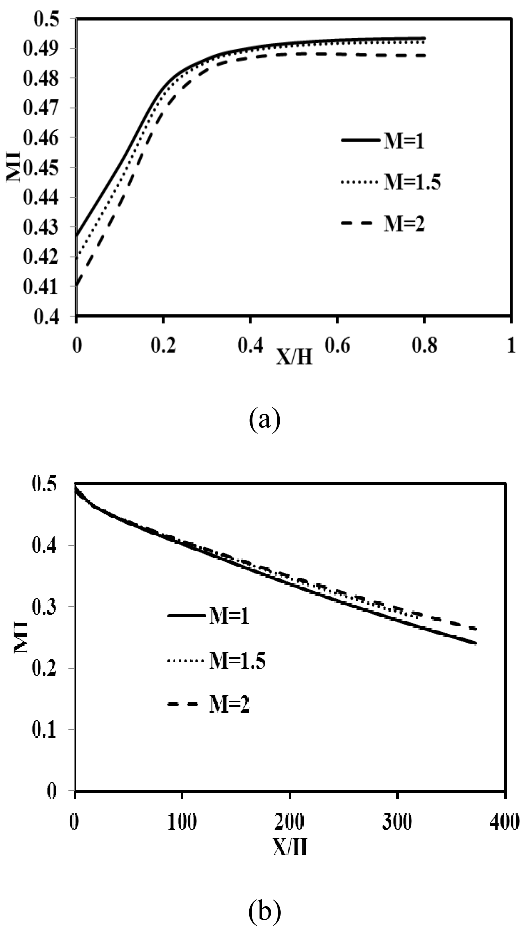



**Fig . 8.** Effect of momentum ratio on mixing index (a) in impinging zone, (b) along the channel, Re=100, H/D=2, n=0.8229.

## 5. Conclusions

In this study, numerical simulations were carried out to analyze hydrodynamics and geometry effects (i.e. Reynolds number, impinging angle, flow behavior index and momentum ratio) of two-dimensional laminar one-way opposing jets of shear-thinning fluids on thermal mixing behavior of these systems. According to this study, the following conclusions can be given:

(1) By increasing the Reynolds number, thermal mixing behavior of steams in impinging zone was improved. However, augmentation of Reynolds number led to decreased mixing index along the channel.

(2) Flow behavior index had an interesting effect on thermal mixing. In impinging region, increase of mixing was observed as flow behavior index increased. There was the same behavior along the channel. Improvement of the thermal mixing with increasing flow behavior was due to higher diffusion of the two jets into each other (in impinging region) and larger residence time of fluid particles (along the channel).

(3) Smaller impinging angles resulted in enhancing thermal mixing in impinging region and along the channel.

(4) Increasing the jets' momentum ratio had a positive effect on thermal mixing in impinging region. However, it led to a reverse effect along the channel.

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