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NUMERICAL INVESTIGATION OF CONVECTIVE HEAT TRANSFER AND FLUID FLOW IN A CHANNEL WITH TWO SEMI -CIRCULAR SHAPED OBSTACLES

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Keywords
Heat Transfer;
Enhancement;
Turbulent;
Semi-circular;
Numerical.

Abstract
In this study, convective heat transfer and fluid flow in a channel with two semi-circular obstacles has been numerically investigated under uniform wall temperature boundary condition. The Reynolds number, in the turbulent flow regime, is chosen 10,000-40,000. The working fluid is taken air with Pr=0.71. The channel height and length are taken 4 and 32 times of the semicircular body diameter, respectively. The location of the bodies is maintained from inlet at 4D and 8D distance.The bodies are set at 2D distance from the channel walls. The Navier- Stokes and energy equations have been solved using Simple algorithm and Standart k-ε formulation for turbulent flow regime. The governing equations are solved using the commercial code Fluent. Rectangular grid is used over the domain. The distribution of Nusselt number and skin friction coefficient on the channel wall are reported depending on Reynolds number. The average Nusselt numbers and skin friction coefficients with and without obstacles are presented comparatively.

YARI DAİRESEL İKİ ENGEL YERLEŞTİRİLMİŞ BİR KANAL İÇERİSİNDE KONVEKTİF ISI GEÇİŞİ VE AKIŞIN SAYISAL İNCELENMESİ

Anahtar Kelimeler
Isı geçişi;
İyileştirme;
Türbülans;
Yarı-dairesel;
Sayısal.

Özet
Bu çalışmada, sabit duvar sıcaklığı altında içerisine iki adet yarı dairesel engel yerleştirilmiş bir kanal içerisinde konvektif ısı geçişi ve akışı sayısal olarak araştırılmıştır. Türbülanslı akış rejiminde Reynols sayısı 10,000-40,000 aralığında seçilmiştir. Akışkan sudur (Pr=0.71). kanal yüksekliği ve boyu engel çapının (D) sırasıyla 4 ve 32 katıdır. Engeller girişten engel çapının 4D ve 8D mesafeye konulmuştur. Engeller kanal duvarlarından 2D uzaktadır. Navier-Stokes ve enerji denklemleri için Simple algoritması ve türbülans modeli olarak Standart k-ε formülasyonu kullanılmıştır. Korunum denklemleri Fluent programıyla çözülmüştür. Geometri üzerinde dikdörtgen ağ yapısı kullanılmıştır. Kanal duvarındaki Nusselt sayısı ve sürtünme katsayısı dağılımları Reynolds sayısına göre verilmiştir. Ortalama Nusselt sayıları ve sürtünme katsayıları, içinde engel olan ve olmayan kanal için karşılaştırılmalı olarak sunulmuştur.

1. Introduction

In recent years, improving of heat transfer is a vital object for researchers, because of energy and material saving. In process industries and engineering systems, there exist various applications of heat transfer in channels. In this type channels, improving heat transfer processing is focus of interest naturally. The improving studies of heat transfer have been tried by using several shaped geometries inserted in the channel. The presence of the bodies cause of separation and reattachment, therefore; turbulence kinetic energy and naturally the heat transfer increases on the channel wall.
Abbasi et al. [1] studied numerically heat transfer (Re=100) using a triangular prism element in a channel. They indicated that use of a triangular prism in a channel could enhance the heat transfer. Chattopadhyay [2] also studied numerically heat transfer

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and turbulent flow (Re=10,000-40,000) using the same shaped element. This study indicated that the order of enhancement was about 15%. However, as expected, the enhancement was associated with enhanced skin friction. Ugurlubilek [3] researched numerically heat transfer and turbulent flow in the same Re interval with Chattopadhyay [2] using a semicircular element in a channel. This geometry was closer to the geometry of Abbasi et al. [1] and Chattopadhyay [2] to compare. Ugurlubilek [3] indicated that the enhancement of heat transfer with a semicircular element in a channel was about 15%, this value was identical with the channel with triangular prism [2]; but increasing of skin friction coefficient was about 17%; while it was 25% in the channel with triangular prism. In the present work, estimating of turbulent flow and heat transfer with two sequential semicircular element placed in a channel was studied numerically. The geometry was also taken identical with earlier studies [1,2,3] in order to compare.

2. Material and Methods

In this work, the governing equations were solved using the Simple algorithm [4] by Fluent [5] program. The working fluid was air (Pr=0.71).

Contunity equation;

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

Momentum equation in x-direction:

$$\frac{\partial (uu)}{\partial x}+\frac{\partial (uv)}{\partial y}=-\frac{\partial P}{\partial x}+\frac{1}{\mathrm{Re}}\left(1+\frac{\nu_t}{\nu}\right)\nabla^2 u \qquad (2)$$

Momentum equation in y-direction:

$$\frac{\partial (uv)}{\partial x}+\frac{\partial (vv)}{\partial y}=-\frac{\partial P}{\partial y}+\frac{1}{\mathrm{Re}}\left(1+\frac{\nu_t}{\nu}\right)\nabla^2 v \qquad (3)$$

Energy equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(1+\frac{\alpha_t}{\alpha}\right)\nabla^2 T \qquad (4)$$

Where u,v,P,ν and T are x-velocity, y-velocity, pressure, viscosity and temperature, respectively. For calculation of momentum equation, the standart k-ε model (6) was chosen. This model has been successfully applied with engineering applications including turbulent flows in channels. The equations for k,turbulent kinetic energy, and ε, its dissipation rate, are given as:

$$u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}=\frac{1}{\mathrm{Re}}\left(\frac{\nu_t}{\sigma_k}\right)\nabla^2 k+P-\varepsilon \qquad (5)$$

$$u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}=\frac{1}{\mathrm{Re}}\left(\frac{\nu_t}{\sigma_\varepsilon}\right)\nabla^2 \varepsilon - C_1 S_\varepsilon - \rho C_2\frac{\varepsilon^2}{k} \qquad (6)$$

Where σ_k=1 and σ_ε=1.3 are the turbulent Prandtl numbers for k and ε , respectively. C1 = 1.44 and C2 =1.92 are constants (Eq. 6). S_ε is user-defined source term. At the inlet uniform velocity profile (u=constant) has been given. No- slip condition was accepted over the channel and obstacle walls (u=v=0). Adiabatic boundary condition was assumed on each obstacle walls and the upper channel wall so that $\partial T/\partial n=0$ where n is the normal to the wall.The temperature of the bottom wall and the inlet temperature was taken as constant, 450 K and 289 K, respectively. The solutions were accepted to convergence when the residuals values were 10-5 for all the variables (P,T,u,v,..).

The ratio of the semicircular obstacle diameter (D) and the channel height was 0.25. The channel length was 32D, the location of two semicircular obstacles were maintained at 4D and 8D from the inlet channel, respectively.

The rectangular grid was applied throught the geometry. Grid indepentent solution was obtained by comparing the solution for different grid levels. The total number of nodes was 29 196 for the geometry with two semicircular obstacles. Because the obstacles influenced importantly to the flow, the geometry was splitted three zones(Figure 1). It has been applied finer grid near two obctacles and the channel walls due to importance of the boundary layer, as shown in Figure 1.

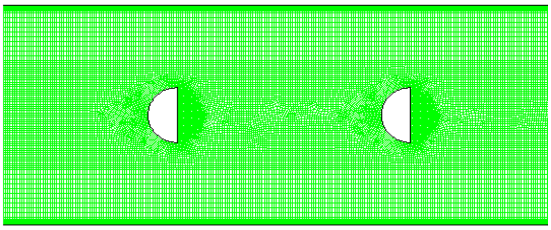

Figure 1. Grid structure for the channel with two obstacles.

Two parameters investigated in this study are Nusselt number and skin friction coefficient. The heat transfer performance is described by Nusselt number which can be found by the local temperature gradient on the channel wall as:

$$Nu_x = -\frac{\partial T}{\partial y} \quad (7)$$

The average Nusselt number can be obtained by

$$Nu_{av} = \frac{\int_0^L Nu(x)dx}{L} \quad (8)$$

where L is the length of the channel. The skin friction coefficient which influences the pumping power is given as:

$$C_f = \frac{\tau_s}{\rho u^2{}_m} \quad (9)$$

Where τ_s, ρ and u_m are the wall shear stress, density and the mean velocity of the fluid, respectively. The Nusselt number and friction factor for the smooth channel are obtained with the correlations of Dittus Boelter and Petukhov (7) found in the open literature for turbulent flow.

Correlation of Dittus Boelter;

$$Nu_{av} = 0.023\mathrm{Re}^{4/5}\,\mathrm{Pr}^{1/4} \quad (10)$$

Correlation of Petukhov;

$$f = (0.7904 \ln \mathrm{Re} - 1.64)^{-2} \quad (11)$$

In this study, the channel length was quite short for the fully developed flow, therefore; the Nusselt number can be calculated from

$$\frac{Nu_{av}}{Nu_{fd}} = 1 + \frac{C}{(L/d_h)^m} \quad (12)$$

where the constants of C and m are related to Pr, Re, entrance zone and entrance feature [7].

3. Result and Discussion

The velocity magnitude contours of the flow near the two obstacles was showed in Figure 2. It can be seen that the flow stream divides itself in two stream because it crashed each semicircual obstacles and combines after the obstacles.This situation causes the higher turbulence, therefore; the heat transfer rate increases.

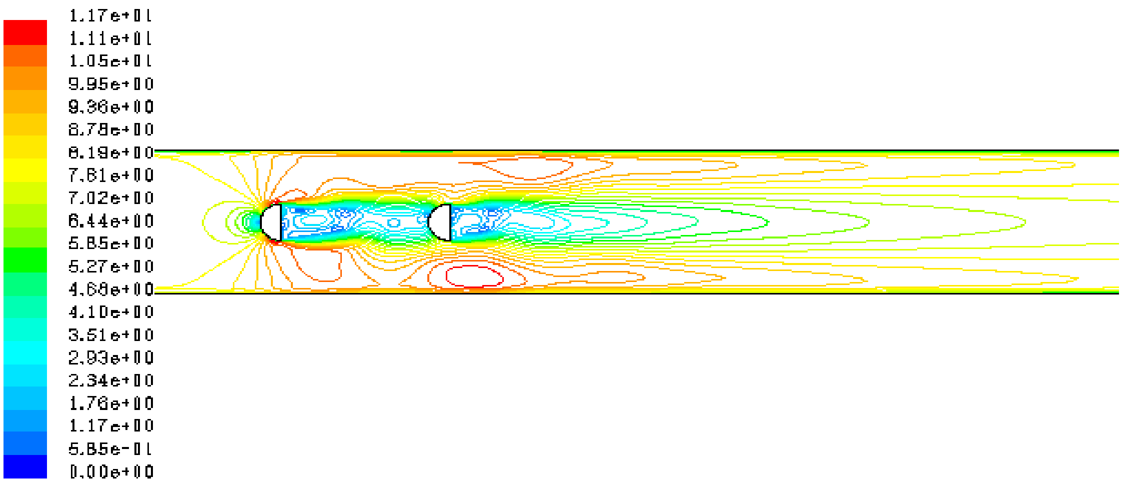

Figure 2. Velocity magnitude contours around two semicircular obstacles (Re=40000).

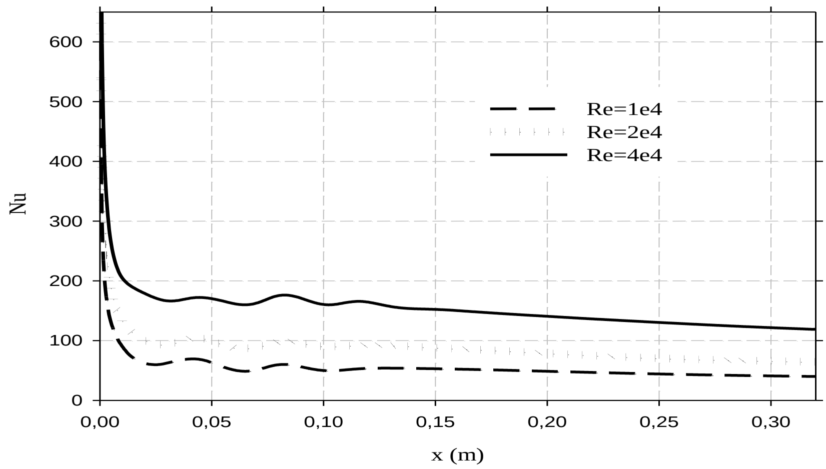

Figure 3. Distributions of Nu along the channel wall at Re=1e4-4e4.

Heat transfer rate distribution at different Re in presence of the two obstacles is shown in Figure 3. It can be seen that the patterns are identical. The heat transfer magnitude increases too, when Re increases.

Table 1 briefes the heat transfer rate at Re=10 000-40 000. It can be seen from the table that the highest enhancement of average Nu number is obtained at Re=10 000 in a channel when two semicircular obstacles are present. While Re number increases, this enhancement rate decreases. Therefore; it can be observed that the presence of the obstacles doesn't create a big enhancement of the heat transfer at the higher Re number than 10 000.

Table 1. Comparison of Nu (with and without obstacles)

Re	Nuav (without obstacles) (Eq. 12)	Nu (with obstacles) (This study)	Enhancement (%)
10000	43.70	58.05	32.82
20000	76.09	88.12	15.80
40000	132.48	148.78	12.29

It is certain that the enhancement of the heat transfer is associated with skin friction leading to higher pressure drop. The distribution of Cf is presented Figure 4, where it is clear that the presence of two semicircular obstacles increases at its location skin friction on the channel wall because of the counter rotating vortex pairs which occur two times.

The increasing in Cf at the channel exit at Re=10 000 is about 47% according to the plane channel (Table 2.) It can be seen from the table that while Re number increases the increasing of skin friction coefficient decreases according to the channel without obstacles

Table 2. Comparison of skin friction coefficient at the channel exit (with and without obtacles)

Re	Cf (without obtacles) (Eq. 11)	Cf (with obtacles) (this study)	Increasing of Cf (%)
10 000	0.0078	0.0116	47
20 000	0.0065	0.0086	31
40 000	0.0055	0.0062	12

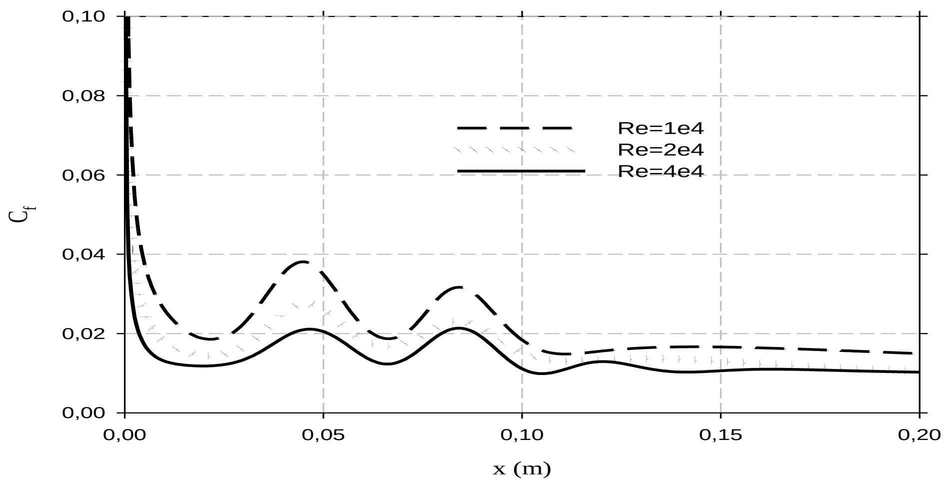

Figure 4. Distribution of Cf along the channel wall at Re=1e4-4e4.

4. Conclusion

As a result; in this paper, calculation of heat transfer and turbulent flow in a channel with two semicircular obstacles was obtained numerically using Fluent commercial code [5]. The highest enhancement of heat transfer is about 33% at Re=10 000. However, as expected, the enhancement is associated with increased skin friction, this value is about 47%. The increasing of Re number (upper than Re=10000) doesn't effect the heat transfer importantly. The study can be extended about Re=10 000 at small Re intervals so as to find the optimum enhancement of heat transfer. The effect of three-dimensionality to the flow field can be investigated in future.

Conflict Of Interest

No conflict of interest was declared by the authors.

5. References

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