



Enhancement of Heat transfer and Pressure drop in a Channel by grooving the Walls

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Abstract

Surface heat transfer and friction coefficients of a channel with laminar air flow through it and with walls set to different constant temperatures have been investigated numerically. Validity of results investigated in a comparison with previous existing experimental data. Effect of two parameters, groove depth to channel height (e/H) and groove width to channel height (w/H) been investigated in different Reynolds numbers. The e/H ratio was between 0.5 and 0.8 and w/H ratio was between 1 and 2.5. Reynolds number of flow was set between 100 and 1760. Using grooves on a channel wall causes an increase in local and global nusselt numbers of it but also causes a pressure penalty too. It is necessary to investigate the conjugate effect of heat transfer improvement and increased pressure drop to see if a method is efficient or not. The results have been compared to find the best efficient configuration of placing grooves.

Keywords: Enhanced heat transfer, grooved channel, Energy consuming optimization

1. Introduction

Fossil fuels have been our main and almost only energy source on earth for many years. Some day there was no concern as oil and gas were easy to drive and use and it seemed that the resources are infinitive. But today we have to deal with the fact that fossil fuels are becoming increasingly limited in supply due to inordinate use of them. It will even get worse when we add the everyday increasing threat of global warming to the situation. We have an energy crisis and a global warming to

face and we have to find a solution as fast as possible.

The solution is energy management. To deal with the threat that we are facing is mostly a matter of getting the best out of present resource and devices rather than searching for some alternative sustainable energy while it's indispensable but time consuming.

Energy management means improving instruments that are working right now to consume energy in an efficient way. Maybe the resulted energy saving won't be much but if we



add all the effects around the world it will lead to a huge amount of resources saved every year.

Heat exchangers and Heat transition instruments is one of the main applications which have been under efficiency improvement studies. A part of these studies is centralized on improving heat transfer between a channels surface and the fluid that flows through the channel. In fact there are many approaches applied to this field right now. Such as using different kinds of turbulators and vortex generators on channel or tubes surface. Using ribbed wall channels is one of the ways to turbulate the flow inside a channel and increase heat transfer between channel wall and fluid. But as almost all of other above-mentioned methods it makes some extra pressure drop inside the channel which is not a wish of us. It is necessary to investigate the conjugate effect of heat transfer improvement and increased pressure drop to see to see if a method is efficient or not.

A similar but opposite method to ribbing the wall is grooving it. This method not only doesn't cause any extra pressure drop inside the channel but also decreases the pressure drop too. Yet there are not many studies published about this method maybe because of rather less heat transfer improvement caused in this method. It is proper to pay an extra attention to the method while it provides us with two positive effects of more heat transferred and less pressure drop occurred simultaneously.

Many different studies have been published about effect of ribbed walls on heat transfer enhancement from a channel. Effect of flow properties (such as Reynolds number) [1, 2], channel properties (aspect ratio, number of

ribbed walls, thermal boundary conditions and ...) [3-6] and turbulator properties (height, width, spacing, substance and ...) [7-10] have been investigated by many authors. Studies about combined effect of these properties and optimization of properties are available too. But there are much fewer studies available about grooved walls. Why? This question can be answered if we track newer publications about rib turbulators that concentrate on application of method on internal cooling of gas-turbine blades [11]. Enhancement of heat transfer in this application is much more important than pressure drop. So ribbing is a more desirable method than grooving here as it improves heat transfer more. But there are applications that pressure drop have more importance there, Heat exchangers namely.

Yet there are some papers published about grooved walls. First Ghaddar et al. [12] investigated properties of incompressible air flow in a grooved duct. Other authors such as Sunden et al. [13], Pereira et al. [14] and Farhanieh et al. [15] continued the job and published experimental and numerical studies on the topic. They showed complex flow patterns such as separation, recirculation, reattachment and deflection. There are also some newer papers that show effect of different groove properties on thermal enhancement and find an optimized case as well. For example Bilen et al. [16] published a paper about effect of groove shape on flow characteristics. They also optimized the conditions using minimization of entropy generation. It is needed to investigate other properties of grooved channel flow more.

In this paper we study surface heat transfer and friction coefficients of a channel with laminar air flow through it and with walls set to different steady temperatures, numerically. Effect of two parameters, groove depth to channel height and groove width to channel height been investigated on heat transfer and pressure loss in different Reynolds numbers. Finally we compare nusselt numbers and pressure drop of grooved wall channel with smooth wall case to find an optimized situation of grooving.

2. Statement of the Problem

Air flow characteristics in a two-dimensional duct have been investigated numerically. The entrance length of duct assumed to be long enough so that flow is fully developed in main section of the duct. The walls of duct are kept at uniform but different temperatures. The upper wall is smooth at temperature of 300 K when lower one is grooved at temperature of 330 K. The flow assumed to be incompressible and laminar. Air enters the duct with temperature of 300 K.

Channel height (H) was 0.01 m and constant. While groove depth (e) and channel width (w) change so that e/H and w/H ratios change between 0.5 to 0.8 and 1 to 2.5, respectively. The main section length of duct is 0.22 m as shown in Fig. 1. An extra entrance length should be added before main section to have fully developed velocity profile at the beginning of main section. Also it's needed to add an extra length after main section to avoid back stream effects on the flow field.

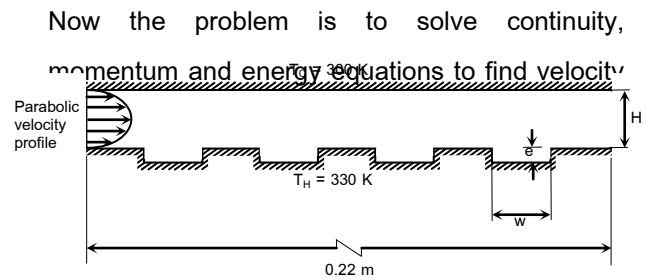


Fig.1 a schematic view of channel's main section

3. Governing Equations

Governing equations to be solved here are continuity, momentum and energy equations. Assumptions of steady state, constant fluid properties, no viscous heating and no natural convection are made here to simplify the problem. These equations are as the form below:

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (3)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho c_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

4. Numerical method

A finite-volume method with fixed coordinates was used to solve the governing equations. Staggered grid used and momentum equation solved for X and Y directions in order to find velocities in each direction. SIMPLEC method was employed as it was needed to solve velocity-pressure coupling. Hybrid upwind/central difference scheme been applied to convective terms when central difference scheme been applied to diffusive terms. Finally TDMA-based

algorithms used to solve the discretized equations.

The boundary conditions are no-slip and constant temperature at walls. To avoid a long solution process we don't enter entrance and exit length in numerical model. Instead it is assumed to have fully developed velocity field at the inlet. Temperature field at inlet is uniform. Also the condition of zero gradients was applied to duct outlet.

The prandtl number was set equal to 0.72 and fluid properties assumed to be constant. Properties of air at 315 K been used when necessary. An under-relaxation factor of 0.5 been used for better convergence. Grid size was set enough small so that it doesn't have a significant effect on results of numerical solution.

5. Data Reduction

Normalized nusselt number and friction factor on channel wall were used to compare heat transfer and pressure drop properties in different cases.

Nusselt numbers was normalized by the nusselt number of fully developed laminar flow in similar smooth duct. T_b in Eq. (5) is the bulk temperature of fluid.

$$Nu = \frac{\left(\frac{\partial T}{\partial y}\right)_w \cdot D_h}{(T_w - T_b)} \quad (5)$$

Also friction factors were normalized by the friction factor of fully developed laminar flow in a smooth duct. U in Eq. (6) is mean air velocity of the duct.

$$f = \frac{2}{(L/D_h)} \cdot \frac{\Delta P}{\rho U^2} \quad (6)$$

These variables can be calculated locally or globally.

6. Results and Discussion

Governing equation was solved numerically for different cases. Validity of results was tested in comparison with available experimental data. Experimental data published by Farhanieh et al. [17] was used to validate results of numerical solution and there was a good agreement between them. Fig. 2 shows this agreement for one of the test cases.

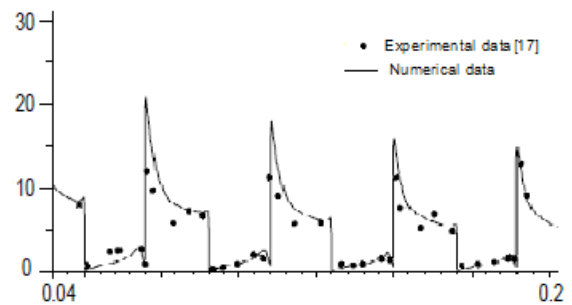


Fig.2 comparison of experimental and numerical nusselt numbers at $Re=620$, $w/H=1$ and $e/H=0.5$

Fig. 3 shows local surface nusselt numbers in the duct for a Reynolds number of 100 and w/H of 1 at different e/H numbers. As it is shown in the figure there is not much difference between local nusselt numbers of different cases.

Fig. 3 also shows how local nusselt number changes along the duct length. It can be seen that local nusselt number drops sharply as flow reaches one of the grooves. It is an effect of lower velocities caused by recirculation zone created inside groove. The recirculation zone can be seen in Fig. 4. After that local nusselt

number increases again and after reaches a peak inside groove, decreases again. Local nusselt numbers out of grooves are higher and it is because of higher flow velocity of main stream than the one of circulated flow inside grooves. Local nusselt number change like ordinary smooth ducts in straight duct area and decreases along flow direction.

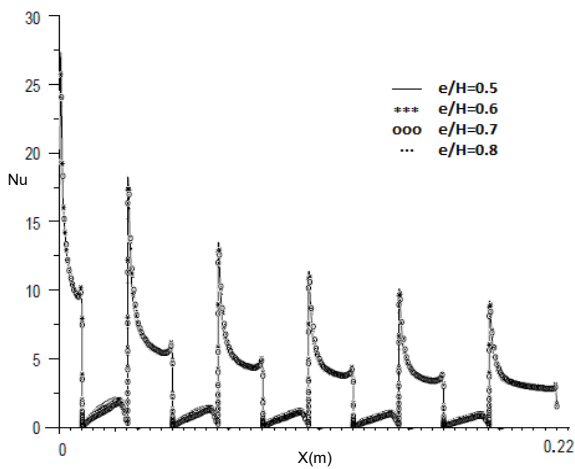


Fig.3 local nusselt numbers at $Re=100$ and $w/H=1$ for different e/H ratios

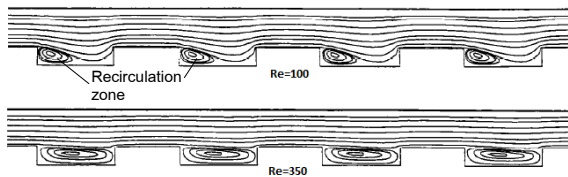


Fig.4 streamlines for two different Reynolds of 100 and 350

Effect of Reynolds number on local nusselt numbers is shown in Fig. 5. Looking to Figs 4-5 shows us that as flow speed or groove depth increases, less fluid can be injected to the groove so local nusselt numbers inside grooves decrease partly. But out of grooves there is a difference. Although increase of Reynolds number increases local nusselt numbers but

increase of groove depth in a constant Reynolds number doesn't have any effect on local nusselt numbers in straight duct area.

As a result of last discussions we can say that increase of groove depth will decrease heat transfer from duct walls for sure. But we cannot decide on effect of Reynolds number on overall heat transfer from duct walls yet. It is needed to compare average nusselt number over duct length to decide.

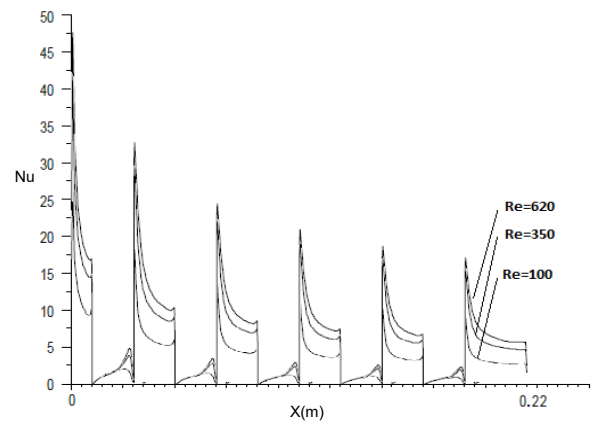


Fig.5 local nusselt numbers for different Reynolds numbers at $e/H=0.5$ and $w/H=1$

We can see in Fig. 6 the effect of w/H change at Reynolds of 100 and e/H of 0.5. As we can see here the effect of w/H change on local nusselt numbers is stronger than e/H effect.

Local nusselt numbers increase w/H ratio increases from 0.5 to 2. But after that when we increase w/H from 2 to 2.5, local nusselt numbers decrease. It seems that it is necessary to investigate effect of w/H on heat transfer from channel walls by use of average nusselt numbers too.

Increasing e/H also effects pressure drop in channel too. As groove depth increases local friction factors decrease. It is a result of less flow entered to groove too. So we can expect that

increasing flow speed would have similar effect on local friction factor inside the grooves. But that will increase friction in straight duct area that will lead to an increase in overall pressure drop inside channel. So it can be said that increasing groove width will lead to a decrease in pressure drop inside the duct but we cannot judge about effect of Reynolds number on pressure drop unless we compare overall pressure drop inside the channel.

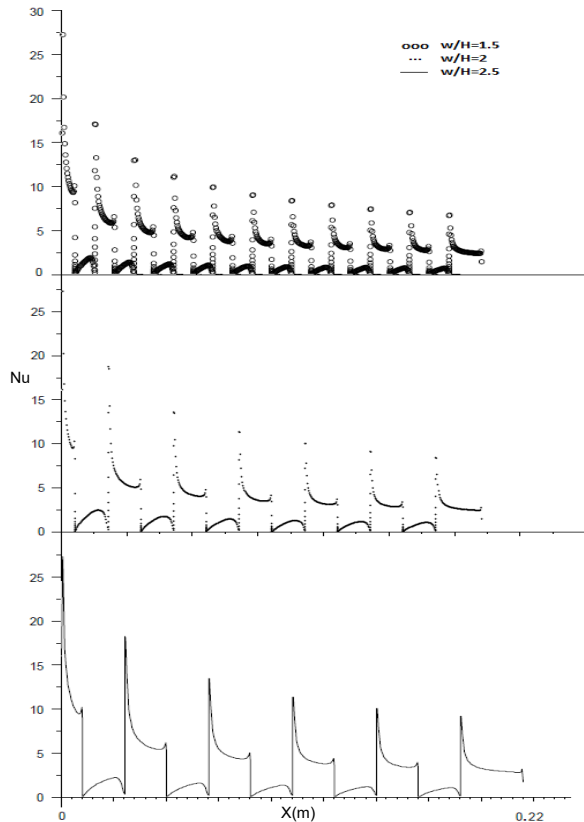


Fig.6 local nusselt numbers at Re=100 and e/H=0.5 for different w/H ratios

Fig. 7 shows a comparison between ratio of pressure drops of grooved and smooth ducts in different Reynolds numbers. The smooth duct pressure drop was calculated for a duct with height of grooved duct plus depth of the groove. As it can be seen there is a minimum at

Reynolds of 600 and after that the ratio increases as Reynolds number goes higher.

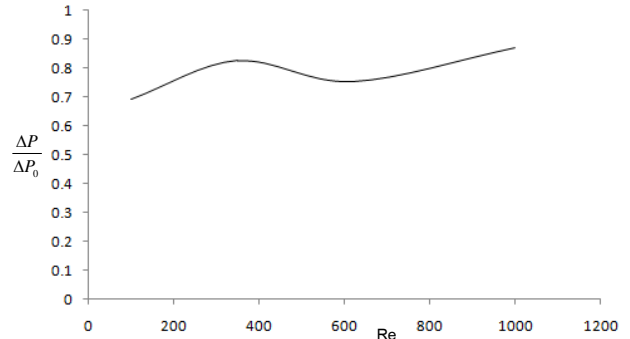


Fig.7 $\frac{\Delta P}{\Delta P_0}$ ratio in a duct for different Reynolds numbers at e/H=0.7 and w/H=1.5

We discussed earlier about effect of groove depth on pressure drop and heat transfer from a duct. It has been cleared that increase of groove depth result to a decrease in heat transfer from channel wall and decreases pressure drop too. But difference of pressure drop in different groove depths is not sensible. So we realize that increase of groove depth will result to waste of more energy and is not desirable.

But we have to study the effect of groove depth on pressure drop and heat transfer at the same time. Fig. 8 helps us to find a case that we have least energy loss in duct.

If in a duct average nusselt number increase and pressure drop decrease happen at the same time then energy saving will be guaranteed. So in Fig. 8 best thermal enhancement will happen when graph reaches its minimum. Best case is w/H=2 and we will have least energy loss at this case. In this case we have least pressure drop and one of the most heat transfer enhancements happen at the same time.

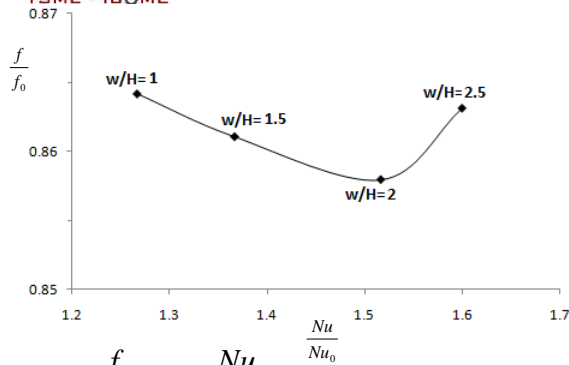


Fig.8 $\frac{f}{f_0}$ with $\frac{Nu}{Nu_0}$ at $Re=100$ and $e/H=0.5$ for different w/H ratios

Pressure drop and heat transfer in a grooved duct with different e/H , w/H and Reynolds numbers been investigated numerically. Results show that increasing e/H ratio will cause in a very little enhancement in pressure penalty when decreases heat transfer from duct wall more intensively. But we can find an optimum value for Reynolds number and w/H ratio that decreases the energy loss. Energy loss is a combination of fractional and thermal energy loss. By investigating conjugate effect of these elements we can find Reynolds number of almost 600 and w/H ratio of almost 2 as best optimum values in a 2-D grooved duct.

We should pay attention to the fact that Reynolds numbers less than 600 will cause less pressure drops. But also won't let us to take advantage of positive increased nusselt numbers effect. Also w/H ratios more than 2 will lead us to more heat transferred from channels wall. But we should consider the larger amount of pressure drop this will cause in the duct. So optimum values found and mentioned above have been found by the assumption of equal importance of pressure drop and heat transfer from channels wall.

7. Conclusions

Thermal enhancement of a duct by grooving one of its walls been investigated numerically. Results been compared with smooth wall duct and with each other in order to find an optimum case with most energy consuming enhancement.

Results show that increase of e/H ratio won't lead to an enhancement in energy consuming although it decreases pressure drop slightly. But increase of w/H ratio will improve energy loss from the duct walls. Best case happens at an e/H ratio equal to 2. Also there is an optimum value for Reynolds number of the flow. We will have least energy loss caused by friction at Reynolds number of almost 600 while at this case we have a rather high heat transfer enhancement too.

8. References

- [1] Chandra, P.R, Alexander, C.R. and Han, J.C. (2003). Heat transfer and friction behaviors in rectangular channels with varying number of ribbed walls, *Heat and Mass Transfer*, vol. 46, pp. 481–495
- [2] Promvonge, P., Chompookham, T., Kwankaomeng, S. and Thianpong, C. (2010). Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators, *energy Conversion and Management*, vol. 51, pp. 1242–1249.
- [3] Arun, K. and Prabhu, S.V. (2007). Effect of Aspect Ratio, Channel Orientation, Rib Pitch-to-Height Ratio, and Number of Ribbed Walls on Pressure Drop Characteristics in a Rotating Channel with Detached Ribs, *Rotating Machinery*, vol. 46, pp. 481-495.



- [4] Park, J.S., Han, J.C., Huang, Y. and Ou, S. (1992). Heat transfer performance comparison of five different rectangular channels with parallel angled ribs, *Heat and Mass Transfer*, vol. 35, pp. 2891-2903.
- [5] Nonino, C. and Comini, G. (2002). Convective heat transfer in ribbed square channels, *Num Methods for Heat & Fluid Flow*, Vol. 12(5), pp. 610-628.
- [6] Schüler, M.S., Neumann, O. and Weigand, B. (2009). Experimental investigations of pressure loss and heat transfer in a 180° bend of a ribbed two-pass internal cooling channel with engine-similar cross-sections, *Power and Energy*, Vol. 223, pp. 709-719.
- [7] Webb, R. (1994), *Principles of Enhanced Heat Transfer*, John Wiley & Sons, New York.
- [8] Huang, R. F., Chang, S. W. and Chen, K. H. (2007). Flow and Heat Transfer Characteristics in Rectangular Channels with Staggered Transverse Ribs on Two opposite Walls, *Heat and Mass Transfer*, vol. 129, pp. 1732-1736.
- [9] Han, J.C. (1984). Heat Transfer and Friction in Channels with Two opposite Rib-Roughened Walls, *Heat Transfer*, vol. 106, pp. 774-781.
- [10] Tsia, J.P. and Hwang, J.J. (1999). Measurements of heat transfer and fluid flow in a rectangular duct with alternate attached-detached rib arrays, *Heat and Mass Transfer*, vol. 42, pp. 1960-1972.
- [11] Han, J.C., Dutta, S., and Ekkad, S.V. (2000), *Gas Turbine Heat Transfer and Cooling Technology*, Taylor and Francis, New York.
- [12] Ghaddar, N.K., Korczak, K.Z., Mikic, B.B. and Patera, A.Y. (1986), Numerical investigation of incompressible flow in grooved channels, Part 1. Stability and self-sustained oscillations, *Fluid Mech*, vol. 163, pp. 99-127.
- [13] Sunden, B., Trollheden, S. (1989). Periodic laminar flow and heat transfer in a corrugated two-dimensional channel, *Commun Heat Mass Transfer*, vol. 16. pp. 215-225.
- [14] Pereira, J.C.F. and Sousa, J.M.M. (1993), Finite-volume calculations of self-sustained oscillations in a grooved channel, *Computational Physics*. Vol. 106, pp. 19-29.
- [15] Farhanieh, B., Herman, C. and Sunden, B. (1992). Numerical and experimental analysis of laminar fluid flow and forced convection heat transfer in a grooved duct, *Heat Mass transfer*, vol. 36(6), pp. 1609-1617.
- [16] Bilen, K., Cetin, M., Gul, H. and Balta, T., (2009), The investigation of groove geometry effect on heat transfer for internally grooved tubes, *Applied Thermal Engineering*, vol. 36, pp. 753-761.
- [17] Farhanieh, B. and Sunden, B., (1991). Three dimensional laminar flow and heat transfer in the entrance region of trapezoidal ducts, *Numerical Methods in Fluids*. Vol. 7(13), pp. 537-556