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NUMERICAL INVESTIGATION OF TURBULENT FLOW PULSATION IN COMPOUND RECTANGULAR CHANNELS

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ABSTRACT

In the present article, we investigate numerically turbulent flow pulsation through compound rectangular channels. RANS, URANS and LES are employed for unsteady turbulence modelling. Strong large-scale quasi-periodic flow oscillations are observed in most of the channels. Such large-scale flow oscillations in compound rectangular channels are similar to the quasi-periodic flow pulsation through the gaps between fuel rod bundle in nuclear reactor. There is a strong peak in the power density spectrum of the axial velocity component. LES gives better predictions for the axial mean velocity distribution than those of URANS. The large scale cross motions through the rectangular compound channels induce significant heat transfer enhancement of the compound channel flow.

INTRODUCTION

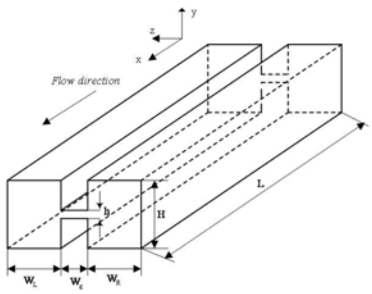
Lyall(1971) measured the axial and secondary flows in ducts composed of two square interconnected sub-channels. He found a strong momentum transfer between the sub-channels by the pulsating cross flow. Meyer and Rehme(1994) measured large–scale turbulence phenomena in the compound rectangular channels with same area connected by gaps of different sizes by hot-wire anemometer. They observed strong large-scale quasi-periodic flow in most of channels investigated. Lee et al.(1998) also performed the experimental work for the compound channels with different areas using LDV. They measured the axial mean velocity and Reynolds stress distributions at the axial positions of 25Dh and 50Dh for the Reynolds number of 60,000.

Present study is aim to investigate numerically the large-scale turbulent flow pulsation through the compound rectangular channels connected by gaps. RANS, URANS and LES are employed for turbulence modelling. Predicted axial mean velocity distributions are compared with Meyer and Rehme's experimental data.

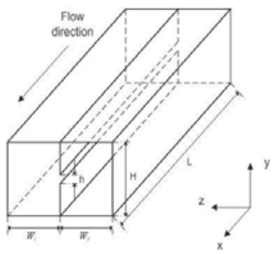
NUMERICAL METHOD

Computational Domain

The computational domains investigated in the present study are 2 types of compound channels as shown in Fig.1. Fig.1(a) show the rectangular compound channels with same area connected by gap. It is a simplified form of subchannel in the nuclear rod bundle assembly. Fig.1(b) shows the compound channel divided by thin partitioner with gap. The flow configuration as shown in Fig.2 is same as Meyer and Rehme's(1994) experiment. The purpose of the computation for the passage of Fig.1(a) is to find the excellent turbulence model for the prediction of pulsating turbulent flow. The flow passage of Fig.1(b) is designed to prove the heat transfer enhancement by pulsating secondary flow. Table 1. shows the geometry parameters for the computational domains. The standard grid employed to cover the cross-section of the compound channels was 246x80x130 for x, y, z directions. Fine grid is distributed in the near wall region and connecting gap. The first grid points near the wall was located at $y^+=0.65$ and $z^+=0.65$ and the minimum grid distance in axial direction was $x^+=3.24$.



(a) type 1



(b) type 2

Fig. 1 Computational domain

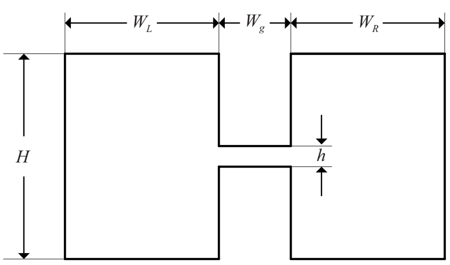


Fig.2 Cross section of experimental investigation in compound channels

Table 1 Geometries Investied (L=50Dh)

No.	H	W_L	W_R	W_g	h
1	0.18	0.136	0.136	0.077	0.01
2	0.18	0.136	0.136	-	0.01
3	0.18	0.136	0.136	-	0.005
4	0.18	0.136	0.136	-	0.015

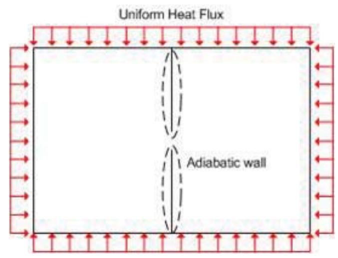


Fig. 3 Thermal boundary condition

Turbulence Model

Turbulence models adopted for RANS are SST(Shear stress transport) and SSG(Speziale, Sarkar and Gatski) models. Smargorinsky model is employed for LES and the time step for all simulation has the values of $1\times10^{-5} \sim 5\times10^{-5}$[sec]

Numerical Method

Supercomputer(IBM P595) parallel computing system was used for the present study. Axial mean velocity at the duct inlet is given by U_b=21.5m/s. No-slip condition and Neumann condition are given at the wall and outlet respectively. Reynolds number based on axial mean velocity (U_b), viscosity(μ), density(ρ) and hydraulic diameter(D_h) is 2×10^5. Thermal boundary condition for the type 2 channel is given by constant heat flux of 2000 W/m^2 for all the wall boundaries.

Convergence of the simulation was determined by the condition of root mean square of mass residual becomes below 10^{-7}.

RESULTS AND DISCUSSIONS

Axial Mean Velocity Distributions

Predicted axial mean velocity distributions at the 6 pathes indicated in Fig.4 are compared with Meyer et al.'s experimental data. Results obtained by employing SSG, SST and LES turbulence models are compared. Experimental data show the hole formation in the core region of compound duct. Melling and Whitelaw(1976) found from their LDV measurements of Reynolds stresses and axial mean velocity of the turbulent flow through square duct that the hole is formed in the core region of the duct due to the secondary flow induced by Reynolds stresses in homogeneity.

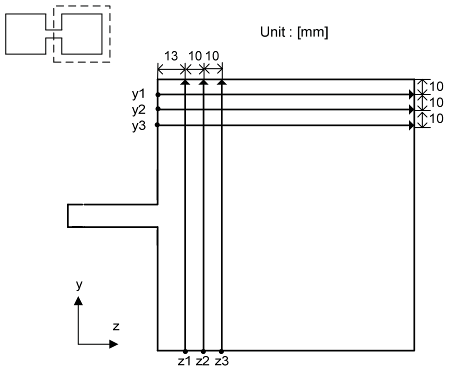
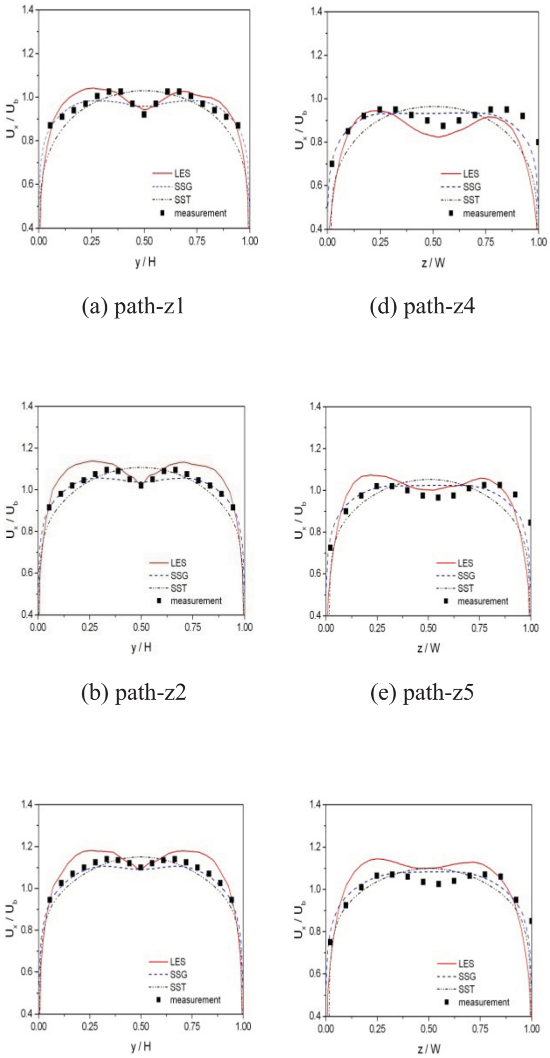


Fig. 4 Path lines for axial mean velocity measurement



(a) path-z1 (d) path-z4

(b) path-z2 (e) path-z5

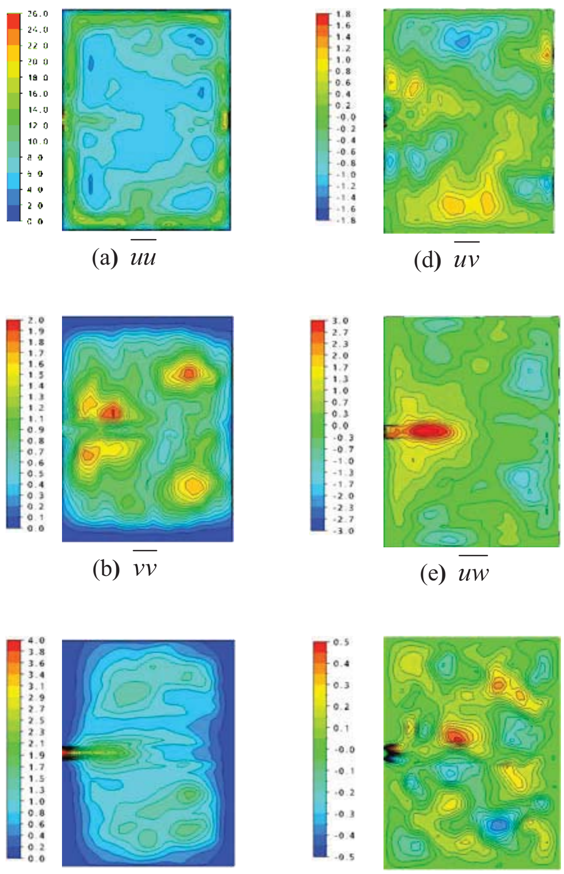
(c) path-z3 (f) path-z6

Fig.5 Distributions of the normalized axial mean velocity (Ux/Ub) along the path lines.

SSG and SST do not catch this hole formation , but LES can catch clearly the hole formation in the core region of compound passage. Therefore, we use only LES model for the heat transfer analysis of pulsating turbulent flow in the type2 flow passage. Fig.5 compares the normalized axial mean velocity distributions(Ux/Ub) at the plane of x=45Dh. Something different axial mean velocity distributions are developed near the gap region of duct for the two types of compound rectangular passages.

Reynolds Stresses Distribution

Pulsating cross flow through gap affect the turbulence characteristics in the compound channels by promoting the flow mixing between the subchannels. Fig.6 shows the Reynolds stresses distributions for type2 channel at the plane of x=45Dh. Increase in Reynolds stresses is shown in the vicinity of gap. This is due to the Reynolds stress generation by the pulsating cross flow near the gap region.



(a) $\overline{uu}$ (d) $\overline{uv}$

(b) $\overline{vv}$ (e) $\overline{uw}$

(c) $\overline{ww}$ (f) $\overline{vw}$

Fig. 6 Statistical Reynolds stresses

Frequency Analysis

Fig.7 shows the time traces of normalized lateral velocity at the center of gap for the 3 different gap widths. Pulsating lateral flow is generated in the compound rectangular channels by the gap. Intensity of pulsation increases by the lateral velocity. The magnitude of pulsation reaches 20% of axial mean veolocity. According to the increase in gap width(h), amplitude of W/U_b decreases. Spectra obtained by FFT analysis of the pulsating flow are shown in Fig.8. Table2 shows the variation of peak frequency with respect to the gap width(h). Peak frequency decrease slowly with the increase in gap width.

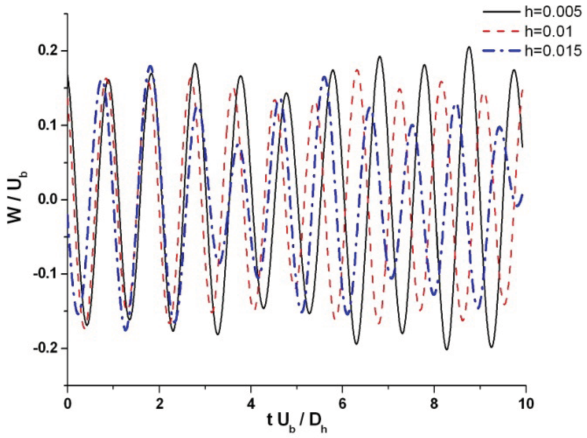


Fig. 7 Time traces of the normalize lateral velocity(W/U_b) at the center of gap

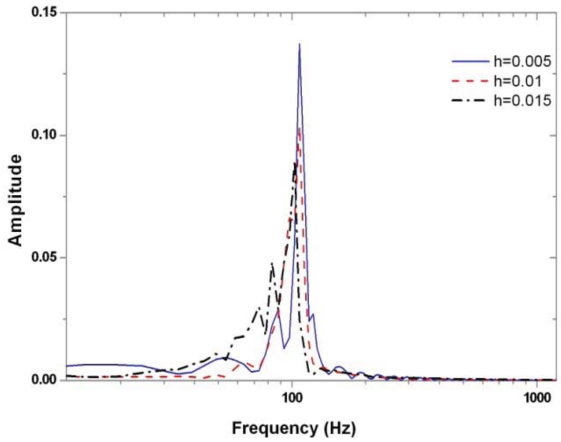
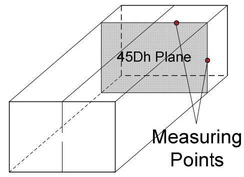


Fig. 8 Spectra on the normalized lateral velocity component W/U_b at the center of the gap

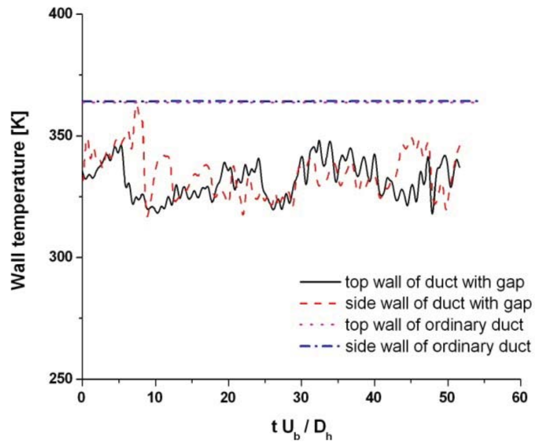
Table 2. Peak frequency with respect to width(h)

h	0.005	0.01	0.015
f_p	107.3	107.2	103.9

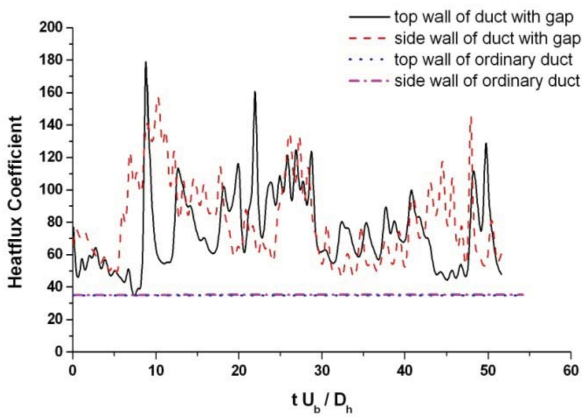
Fig.9 shows the variations of wall temperature and heat transfer coefficient at the top and side walls of rectangular compound channels. Pulsating lateral flow between compound subchannels enhances largely the heat transfer of duct walls. Temperatures of side and top walls of compound subchannels decrease and heat transfer coefficients of the walls increase significantly compared to the ordinary rectangular channel due to the lateral flow pulsation.



(a) Measuring points



(b) Wall temperature at the measuring points



(c) Heatflux coefficient at the measuring points

Fig. 9 Wall temperature and Heatflux coefficient at the measuring points.

Heat Transfer Enhancement

Heat transfer improvement of compound rectangular channels by pulsating lateral flow is investigated. For 3 different gap widths, numerical studies performed to analyze the turbulent heat transfer of the compound channel for constant heat flux boundary condition.

Fig. 10 shows the time variation of averaged wall temperature of compound rectangular channels. Ordinary channel means the rectangular channel without partitioner. In the initial period, the magnitude of pulsation is so weak that heat transfer enhancement effect does not occur upto about 0.4 second. However, according to the development of pulsating flow, mean wall temperature of the channel decreases and large heat transfer enhancement occurs.

In Fig.10, remarkable wall temperature decrease is found at tU_b/D_h=120. This may be due to the turbulent flow mixing by the lateral flow pulsation. Fig.11 show the time variation of overall mean heat transfer coefficient of channels. About 35% increase in heat transfer coefficient is found. Nusselt number in compound rectangular channel is defined by $Nu=hD_h/k$. In the type2 compound rectangular channel, hydraulic diameter(D_h) decreases due to the partitioner so that, in the initial period, Nusselt number of compound channel decrease compared to the ordinary channel. However, after time passing, Nusselt number of the compound rectangular channel increases again and rises to higher value than that of ordinary channel.

Fig.13 show the variation of Nusselt number of fully developed stage with respect to the gap width. With the increase in gap width up to 10mm, Nusselt number increases. However, for the gap width over 10mm, Nusselt number does not increase any more.

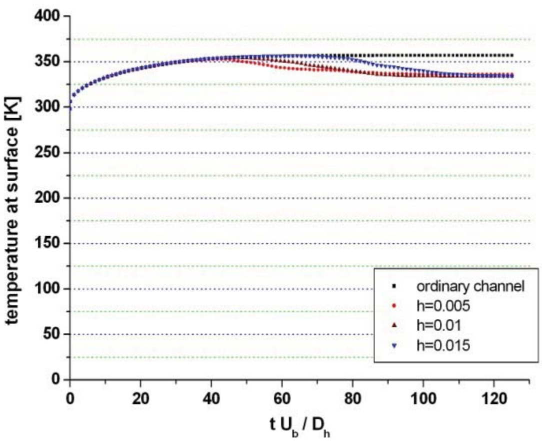


Fig.10 Overall mean wall temperature

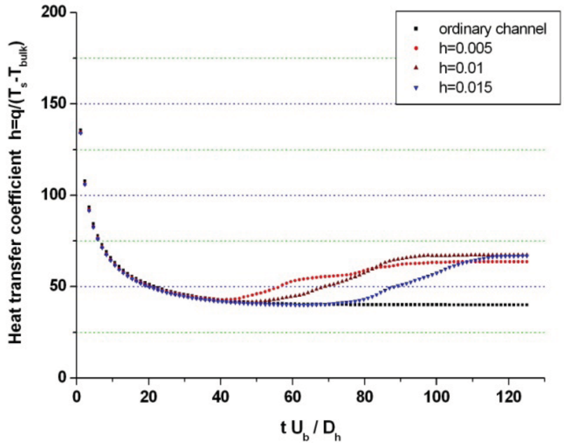


Fig.11 Overall mean heat transfer coefficient of wall

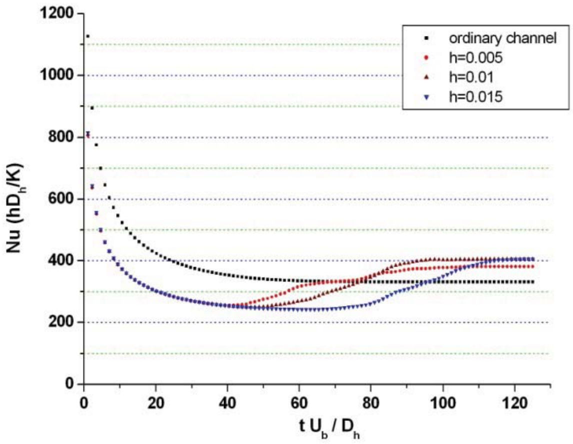


Fig.12 Overall mean Nusselt number of wall

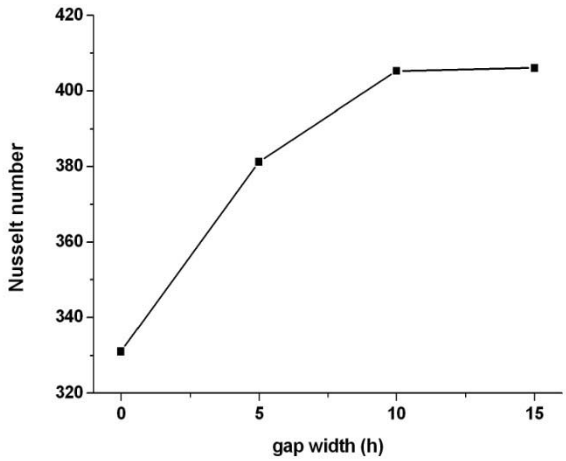


Fig.13 Variation of final stage Nusselt number with respect to gap width(h)

SUMMARY AND FUTURE WORK

In the present study, the characteristics of flow pulsation in the compound rectangular channels connected with gap are investigated numerically. SST, SSG and URANS models and LES are employed for turbulence modelling. Predicted results are compared with Meyer and Rehme's experimental data. Results show that LES give better axial mean velocity distribution. Pulsating turbulent flow induced by gap in the rectangular compound channel increases the turbulent intensity near the gap region. FFT analysis shows the peak frequency of pulsating flow decreases with increase in gap width. About 35% heat transfer enhancement is found due to the lateral flow pulsation. The level of heat transfer enhancement and frequency of compound channel are affected by gap width and depth. More parameter studies are needed for the gap geometry to induce maximum heat transfer enhancement by pulsating lateral flow in the compound channels.

ACKNOWLEDGEMENT

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