Turbulent Heat Transfer of a Finned Plate in a Duct as Tip Clearance Changes

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1. Introduction

Fins are employed to enhance the cooling performance of a system [1-5]. There are a number of studies relevant to geometry of fins. Meanwhile, the studies relevant to tip clearance, have not performed enough, which is the distance between the tips of the fins and the wall. We investigated the optimal tip clearance, which maximizes the heat transfers by experimental and numerical analyses with wider range of Re_{Dh} than the previous studies. The Pr was 2,014, fin spacing, S 2×10^{-3} m, fin height, H 5×10^{-3} m, the fin thickness, t 3×10^{-3} m, the width of the base plate, W 5×10^{-2} m and the length of the base plate, L 5×10^{-2} m. We varied tip clearance and Re_{Dh} from 0 m to 1.5×10^{-2} m and from 4,000 to 8,000 respectively. A joint experimental and numerical analyses were performed for the moderate tip clearances to verify the numerical results. Especially, the numerical method by commercial software FLUENT 6.3.26 was applied for the narrow tip clearances which are very difficult to achieve experimentally. Mass transfer experiments were performed by exploiting the analogy of heat transfer using a cupric acid–copper sulfate (H_2SO_4-$CuSO_4$) electroplating system.

2. Previous studies

2.1 General characteristics of finned plate

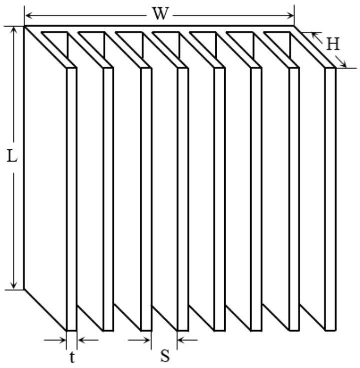

Fig. 1. Finned plate geometry.

Heat transfer at a finned plate is affected by H, S, t, L and W as shown in Fig. 1, as well as flow conditions. Saad A *et al*. [6] investigated turbulent heat transfer of the finned plate by experimentally, varying Re, H, t and S. They reported that the heat transfer enhanced as the Re, S and t increased while H decreased.

2.2 Effect of tip clearance

Dogan *et al.* [4] reported that the total heat transfer enhanced as the tip clearance decreased. Particularly, this phenomenon is intensified as the Re_{Dh} increased. Kim *et al*. [5] and Min *et al.* [7] found optimal tip clearance by experimental and numerical analyses. Bypass flow occurs due to the tip clearance and increases as the tip clearance increased. The bypass flow enhances heat transfer of the fin tips. However, it also impairs heat transfer of the fin grooves.

3. Experiments

3.1 Experimental Methodology

Mass transfer experiments were performed replacing heat transfer experiments based upon analogy [8]. A sulfuric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system was employed as the mass transfer system. A more detailed explanation of the methodology can be found in Chung et al. [9, 10].

3.2 Experiment apparatus and test matrix.

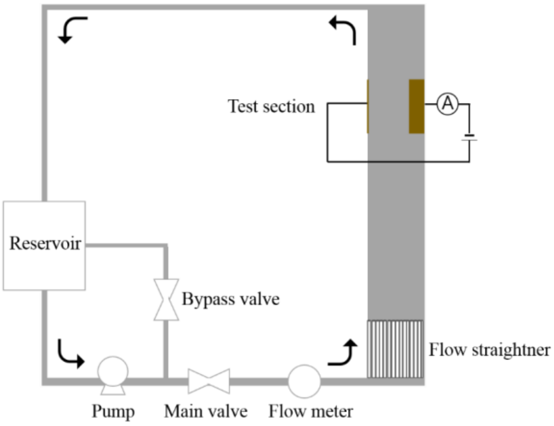

Fig. 2. System circuit.

Fig. 2 shows a schematic diagram of the experimental arrangement. The flow was generated by a pump and passed through a valve, a flow meter, a flow straightener and the test section, and then returned to the reservoir. The flow rate was controlled using the valve, and the bypass line was used to achieve very low flow rates where pump control was not sufficient. The flow straightener was used to reduce the distance required for a uniform flow employed at the upstream of the test section.

Table I : Test matrix for experimental and numerical analyses.

Tip clearance (m)	Re_{Dh}
0 - 3×10^{-3},5×10^{-3},10×10^{-3},15×10^{-3}	4,000, 6,000, 8,000

Table I shows the test matrix for both experimental and numerical analyses. The underlined entries are for the numerical analyses only. The tip clearance and Re_{Dh} were varied with fixed values of $W = L = 5\times10^{-2}$ m, S = 2×10^{-3} m, $t = 3\times10^{-3}$ m, $H = 510^{-3}$ m and $Pr = 2{,}014$. The Sc corresponds to Pr in the heat transfer system. Here we have $Sc = 2{,}014$, as determined by the concentration of the H_2SO_4-$CuSO_4$ solution.

4. Numerical analyses

4.1 Governing equations and boundary conditions

Governing equations and boundary conditions are listed in Equations (1)-(6).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial x}, \tag{2a}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial y}, \tag{2b}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial z}. \tag{2c}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right). \tag{3}$$

$$u=v=w=0 \text{ at all walls,} \tag{4}$$

$$T=T_0 \text{ on heated wall, and} \tag{5}$$

$$T=T_\infty \text{ at the entrance.} \tag{6}$$

4.2 Simulation domain and turbulent model

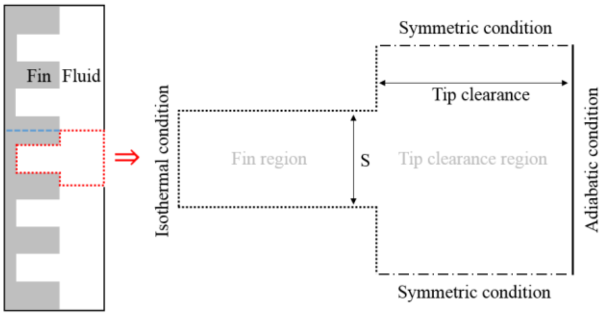

Fig. 3. Simulation domain.

Using commercial software GAMBIT 2.4.6, the 3D single channel of finned plate was generated as shown in Fig. 3. The hexahedral cells were applied and wall y^+ was obeyed by 0.3 due to the enhanced wall treatment was used for the near-wall treatment. The Reynolds Stress Model (RSM) was introduced for turbulent viscous model due to the high Pr of working fluids. The RSM showed the lowest errors compare to the other models at the simple cylinder flow which is able to compare with exist heat transfer correlation at high Pr; 2,014.

5. Results and discussion

5.1 Validation of numerical results

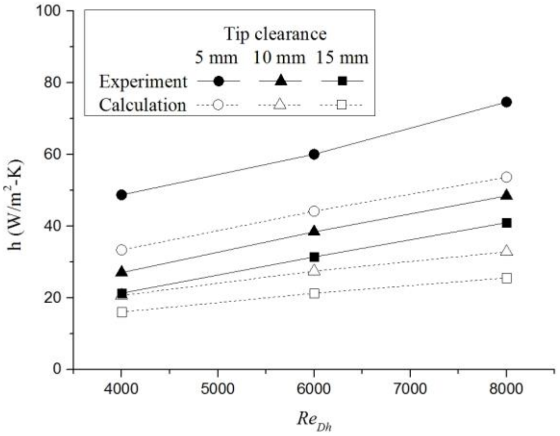

Fig. 4. A comparison of the experimental and numerical results.

Figure 4 shows a comparison of the experimental and numerical results as a function of the Re_{Dh} and heat transfer coefficient according to tip clearances. The maximum error between experiment and calculation was 35%. The errors seem to result from complex geometries and Re_{Dh} inferiority. However, the relative increase in heat transfer coefficient respect to Re_{Dh} has similarity between experiments and calculations. Therefore, we calculated the narrow tip clearance to find optimal tip clearance, which has relativity.

5.2 Influence of the tip clearance

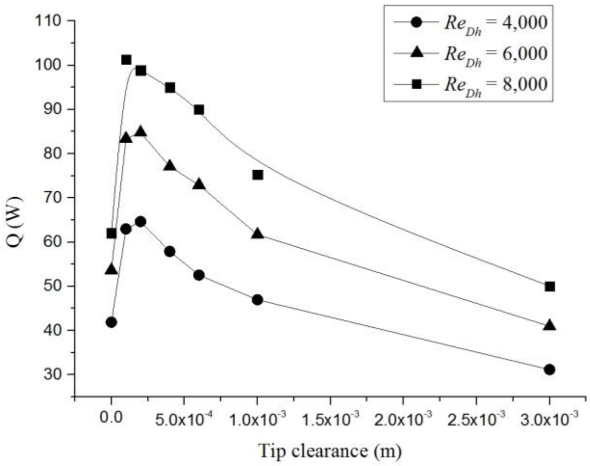

Fig. 5. A variation of Q (W) with tip clearances and Re_{Dh}.

Figure 5 shows a variation of heat (Q) with tip clearances and Re_{Dh}. The Q has maximum value respect to tip clearances regardless of the Re_{Dh}. The Q has minimum value at no tip clearance case as the tips of fins are unable to contribute to heat transfer. The optimal tip clearance is found regardless of Re_{Dh}. Particularly, the larger Re_{Dh} has the smaller optimal tip clearance.

5.3 Phenomenological analyses

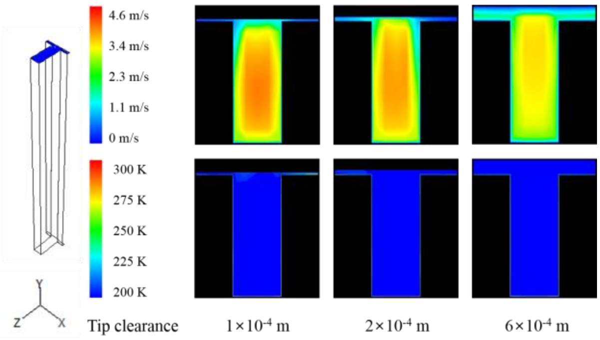

Fig. 6. Velocity and thermal profiles at the trailing edge of the finned plate.

Fig. 6 shows velocity and thermal profiles at the trailing edge of the fin channel and second column shows the optimal tip clearance. The velocity of fin region is decreases as the tip clearance increased and opposite phenomenon causes at the tip clearance region. However, magnitude of the velocity shows great difference between fin and tip clearance region at the optimal tip clearance. Meanwhile, the heat transfer area of the fin region is significantly larger than that of tip clearance region. The thermal boundary layers are have similarity at all tip clearances due to the high *Pr*.

5. Conclusions

Turbulent heat transfers of a finned plate were measured. For an extended range of tip clearance and Re_{Dh} than other studies. A joint experimental and numerical analyses was performed to measure heat transfers. Mass transfer experiments using electroplating system was used and FLUENT 6.3.26 was used for the calculation. For the narrow tip clearances below 5 mm, were investigated by numerical method only. The bypass flow to the tip clearance region contributes to heat transfer area at the tip clearance region and does not contributes that of the fin region. Thus, the optimal tip clearance was founded and it exists vicinity of 0.2 mm.

ACKNOWLEDGMENTS

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