Development of high efficiency heat exchanger for Air-conditioner using optimization technique
(Optimization of slit shape for heat exchanger)

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In this paper, the new technique of the optimization, especially for heat and fluid problems which has a complicated design area of solution that consists of many design variables, is proposed. It is characterized by dividing design area applying data-mining to the sampled dataset, and advancing optimization for every design area. The proposed method is applied to the development of the heat exchanger fin, and the result verifying the validity is reported.

Key Words : Optimization, Data Mining, CFD, Slit Shape of fin, Heat Transfer, Pressure Loss

1. Introduction

In recent years, it has started to be optimized in flow problems with the advance of numerical fluid dynamics[(1)~(3)]. In particular, the optimization on the streamlined-shape which can be done by off-line has often begun to be applied in a design and development for mass production. However, when there are a lot of design variables and the replies are very complicated, a lot of calculations are needed to get optimum solution. To have to use the probability-theory technique like GA (Genetic Algorithm) sometimes makes the reliability of the optimum solution fall. And optimization isn't standardized in a design and development, because there are few ways to examine enormous data an optimization process gave and use it effectively.

In this paper, the new technique of the optimization, especially for heat and fluid problems which has a complicated design area of solution that consists of many design variables, is proposed. The proposed method is applied to the development of the heat exchanger fin, and the result verifying the validity is reported.

2. New process for optimization

The outline of the new optimization process which is used in this paper is shown in figure 1.

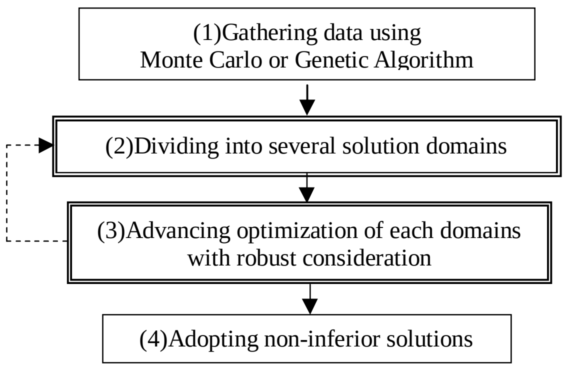


Fig.1 Outline of optimization procedure.

2.1 Data sampling

Much data with the uniform distribution is needed to divide overall design area of solution into several domains. In this paper, design area of solution is divided using RSM (Response surface model) which has second order. When the number of the design variable is set as V_N, the distribution number of the domains is set as A_N, and the number of sampling S_N with high accuracy is

$$S_N \geq 2 \times \left(2 \cdot V_N + {}_{V_N}C_2 + 1\right) \times A_N \tag{1}$$

where ${}_{V_N}C_2$ is the combination function which chooses 2 of combination from V_N. For example, when design variable set 24 and the number of the domains set 6, sampling number S_N will be more than 3900.

2.2 Dividing design area of solution

The outline of the dividing concept which use in this paper is shown in figure 2.

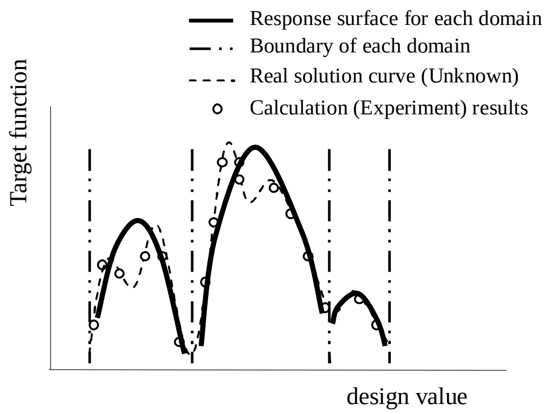


Fig.2 Concept of dividing-domain method.

After dividing design area of solution optionally, RSM is made in each domain. When we use RSM which has second order, the response function is

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} {x_i}^2 + \sum_{i<j} b_{ij} x_i x_j \tag{2}$$

Equation (3), coefficient of multiple determinations is used as the index which estimates the consistency between correlation equation and data which exists actually. This value is set to 1 from 0, and shows that it is moderately good correlation near 1.

$$R_{ad}{}^2 = 1 - \frac{SSE/(n-k-1)}{S_{yy}/(n-1)} \tag{3}$$

where,

Total sum of squares about y :

$$S_{yy} = y^T y - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n} = SSR + SSE \qquad (4)$$

Coefficient of multiple determination :

$$R^2 = \frac{SSR}{S_{yy}} = 1 - \frac{SSE}{S_{yy}} \qquad (5)$$

Square sum of Errors : SSE

Regression Sum of Squares :

$$SSR = b^T X^T y - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n} \qquad (6)$$

Design area of solution is divided repeatedly so that an error of RSM in the each domain may be minimized. In the case, the distance with each data and the center of the domain is calculated by following equation (in case of two dimensions). When the distance is beyond setting and the data exists near the boundary, the data permit to exist in more than one domain(4).

$$D(x, y) = \left(\sum_{k=1}^{\Gamma} (x_k - y_k)^2\right)^{\frac{1}{2}} \qquad (7)$$

2.3 Optimizing for each domain

In the domain where an error of RSM is small, optimization is advanced using the nonlinear mathematical technique. In another domain, optimization is advanced using probability-theory technique like SA or GA. In this step, the optimization which is considered actual development is performed. For example, the design variables which are considered an influential factor are focused, the target function with low priority is added, and robustness is estimated.

2.4 Adopting pareto and reflecting to a design

After design area of solution is renewed and domain is re-divided, pareto is adopted in each domain. And a correlation equation with high accuracy is gathered as the design system in each domain.

3. Applying to the development of the heat exchanger fin

The proposed method which was above-mentioned is applied to the development of the heat exchanger fin, and the result verifying the validity is reported.

3.1 Setting of an optimization problem

Development objectives of heat exchanger are high heat transfer and the low pressure loss. These development objectives are achieved by optimizing the shape of slit which exists between pipes.

3.2 Design variable

The design variables of slit are shown in figure 3.The outside diameter of the fin color(DcA), step pitch(Dp), low pitch(Lp), fin thickness(tf), and fin pitch(fp) is fixed and inlet velocity is set as 1.5 (m/s). The parameters of optimization are position of each slits(Ds), length(Ls), width(Ws), height(Hs), and angles(θ1, θ2).

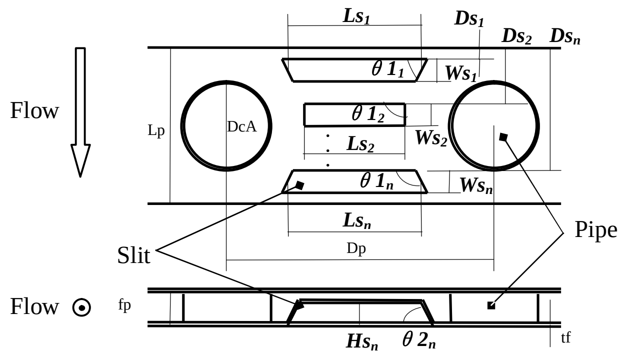


Fig.3 Design variables for fin shape.

3.3 Automatic analysis system for CFD

Flow chart of automatic analysis system made for this study is shown in figure 4. When design variables are established randomly, a lot of combinations of design variables which isn't formed geometrically are made. Therefore parametric program which can define design variable without geometrical error is made. And the input variables of this program are the parameter of this optimization.

Automatic pre and post processing of CFD are used the macro function of Prostar. And a convergence of an analysis is judged by the pressure difference and the temperature difference between inlet and outlet boundary and residual of Star-CD.

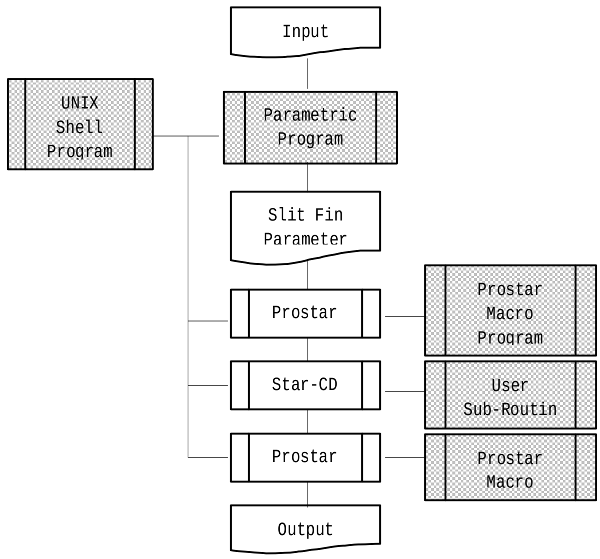


Fig.4 Flow chart of automatic analysis system.

An example of analysis model made by macro program is shown in figure 5. And a relation between mesh size and an accuracy of solution is shown in figure 6.

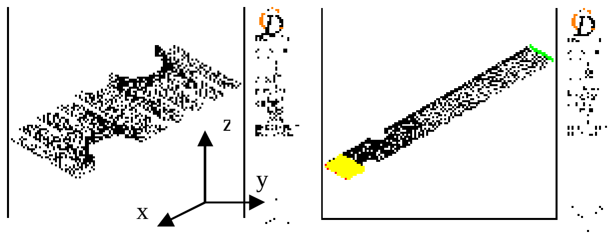


Fig.5 Example of an analysis model.

When inlet velocity is set 2.0 (m/s) from 1.0 (m/s), the number of Reynolds will be about 330 from about 160(equation (8)). This analysis can be handled as laminar flow, so the analysis accuracy improves by doing mesh size small. However increasing on computing time will be a serious problem in optimization which requires many calculations. Large mesh size where an analysis result becomes stable relatively be have to chosen.

$$Re = U \cdot De_c / n \qquad (8)$$

where, U is inlet velocity, ν is kinematical viscosity, Dec is an equivalent diameter of plate fin and tube heat exchanger and is shown by following equation(5).

$$De_c = \frac{4 \cdot (f_p - t_f) \times \left(S_1 \cdot S_2 - \frac{p \cdot d_c{}^2}{4} \right)}{2 \cdot \left(S_1 \cdot S_2 - \frac{p \cdot Dc_A{}^2}{4} \right) + p \cdot d_c \cdot (f_p - t_f)} \qquad (9)$$

where, S_1 is low pitch and S_2 is step pitch.

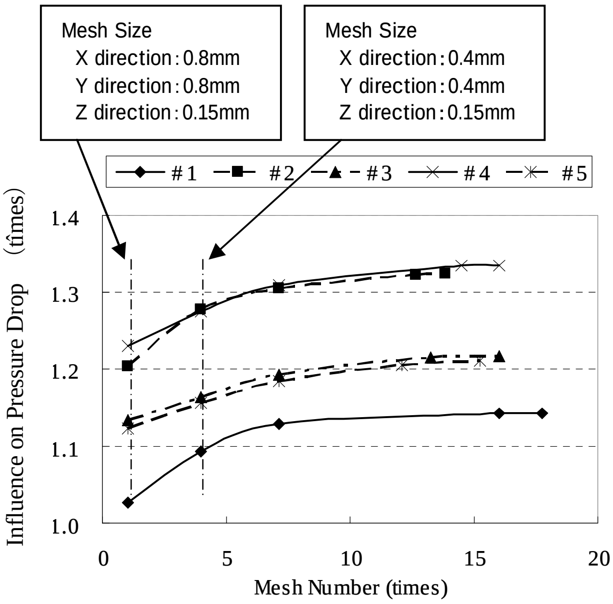


Fig.6 Influence of mesh size.

3.4 Result of sampling and optimization

The 8000 dataset which is sampled by Monte carol and GA in the case of 3 slits are shown in figure 7. This dataset also are divided into 6 domains using the original method which is proposed in this paper. And these dataset are compared with the plate fin (fp=1.2mm) which has same diameter, low pitch, step pitch, fin thickness and different fin pitch (fp=1.5mm). A horizon axis shows the relative ratio of the pressure loss and a vertical axis shows the relative ratio of the heat transfer coefficient.

The result which is optimized using a mathematical method in the each domain is shown in figure 8. In this optimization, reduction in peculiar noise (speed distribution analysis) and improvement of the drainage performance (edge length) are added as the target function. And the robustness is also considered for stability to actual mass production. The data which is sampled by the previous step and the data below the dash-dot-dot has been taken.

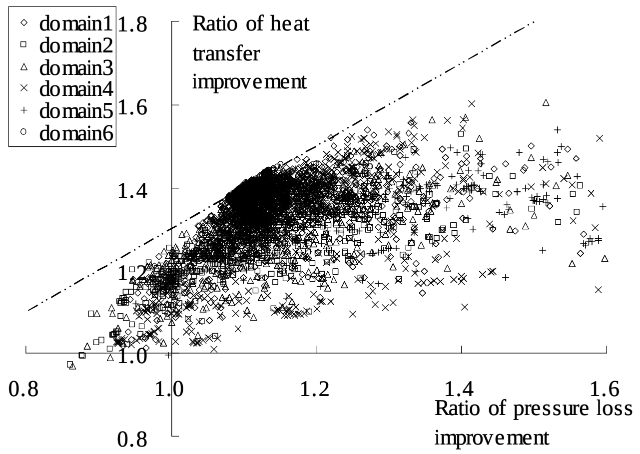


Fig.7 Sampled dataset applied data-mining.

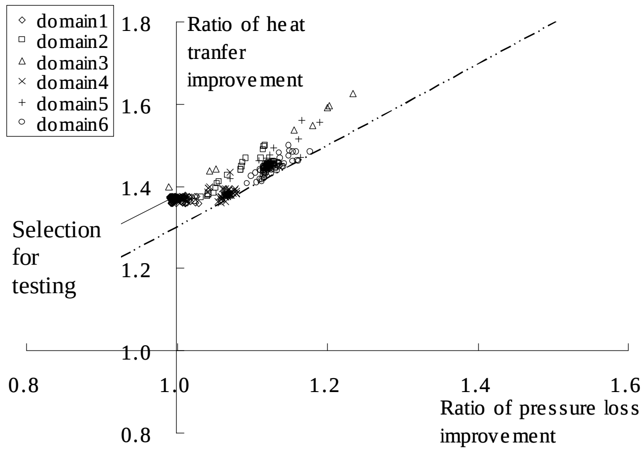


Fig.8 Result of optimization for each domains.

The slit shape determined by this optimization is shown in figure 9. This fin has 2 short and narrow slits in an upstream side, and 1 long and wide slit in a downstream side. It is characteristic that the width of the slit in a downstream side is over 1/3 of the fin color diameter in particular.

Fig.9 Fin shape determined by optimization.

3.5 Verification by an experiment

A conventional slit fin (fp=1.5mm) is shown in figure 10. And comparison of the element performance of the conventional slit and the optimized slit is shown in figure 11. The heat exchanger used for an experiment is 12 steps, 2 lows and 400(mm) of width, and the experimental condition is the standard cooling condition at 1.5 (m/s). And these dataset are also compared with the plate fin (fp=1.2mm).

Fig.10 Conventional fin shape (Samsung Electronics Co.).

An optimized slit is improved about 10% (dry condition) and 25% (wet condition) more than a conventional slit in pressure loss with same heat amount. And when an analysis result is compared with an experimental result in the dry condition, the analysis precision is about +2% in pressure loss and about +3% in average heat transfer coefficient.

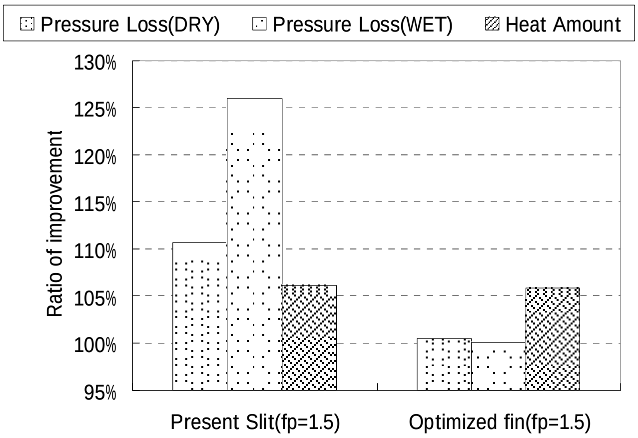
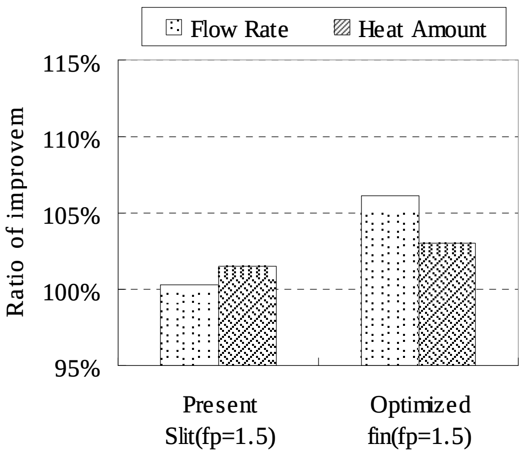
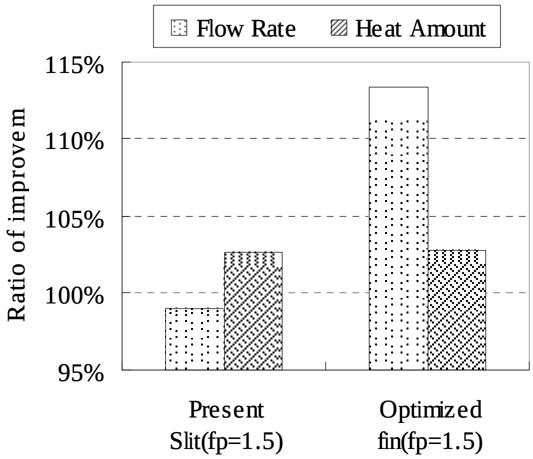


Fig.11 Test results at cooling.

Comparison of the performance of the conventional slit and the optimized slit which is mounted on products (SH09APG, SH12AS4) is shown in figure 12. An optimized slit is improved about 7% (SH09APG) and 15% (SH12AS4) more than a conventional slit in flow rate. Originally the heat amount is increased by increasing of a flow rate. However the heat amount was almost equal because the refrigerant cycle is set to a conventional slit.



(a) Apply to Samsung air conditioner (SH09APG).



(b) Apply to Samsung air conditioner (SH12AS4).

Fig.12 Test results at cooling.

4. Consideration

In this chapter, heat transfer and pressure loss performance of a general slit are explained at first, and the feature about the performance of the optimized slit is analyzed in detail.

The heat transfer coefficient of the general slit is shown by following equation[6].

$$hs = k/Ws \times 0.664 \times \mathrm{Re}_a{}^{0.5} \times \mathrm{Pr}^{0.3} \quad (10)$$

where, k is heat conduction ratio(0.0261W/mk), Pr is Prandtle number(0.72), and Re_a is shown by following equation.

$$\mathrm{Re} = U \times Ws/n$$

Now, the range of slit width (Ws) is defined by following equation.

$$510 \times U \times (fp - tf)^2 \geq hs = 3.914 \times (U/Ws)^{0.5} \times Ws \quad (11)$$

When this is substituted for the equation (10), the heat transfer coefficient of the slit will be

$$hs \geq 0.173/(fp - tf) \quad (12)$$

On the other hand, it is possible to use following equation as the heat transfer coefficient of the fin without slits[6].

$$hb = k/\{(fp - tf) \times 2\} \times 4.3 = 0.056/(fp - tf) \quad (13)$$

When the number of the slit which exists between 1 low is set to Ns, the effective heat transfer coefficient is calculated by an area weighted average of the equation (12) and (13).

$$h_{eff} = hb + (N \times Ws/Ls) \times (hs - hb) \quad (14)$$

And the rate of the average heat transfer coefficient increased by the number of the slit will be following equation.

$$h^* = (N \times Ws/Ls) \times (hs/hb - 1) \geq Ns \times \{1274 \times U \times (fp - tf)^2 / Lp\} \quad (15)$$

Therefore, the heat transfer coefficient is increased with increasing of the number of slit (Ns) proportionally. However, the heat transfer coefficient and the heat transfer amount are not proportional relation. As air goes to a downstream side, the temperature of air will be close to the temperature of fin surface, and the heat transfer amount will become a constant value. Specifically, the heat transfer amount is shown by following equation.

$$Q = r \times Cp \times U \times (fp - tf) \times \{1 - \exp(-NTU)\} \quad (16)$$

where, ρ is density(1.2kg/m^3), cp is specific heat(1004J/kg·K), NTU is the number of transfer unit and shown by following equation.

$$NTU = (Np \times Lp \times h_{eff})/\{r \times Cp \times U \times (fp - tf)\}$$
$$= 0.00166 \times (Lp \times h_{eff})/U \times (fp - tf) \quad (17)$$

where, Np is the number of tube array of the flow direction. H_{eff} is shown by following equation.

$$h_{eff} = 0.056/(fp - tf)$$
$$\times \{1 + Ns \times (1274 \times U \times (fp - tf)^2 / Lp)\} \quad (18)$$

Therefore, the rate of the heat transfer amount increased by the number of the slit is shown by following equation.

$$Q = 1205 \times U \times (fp - tf) \times \{1 - \exp(-NTU)\} \quad (19)$$

$$Q^* = \{1 - \exp(-NTU)\}/\{1 - \exp(-NTU_0)\} - 1 \quad (20)$$

NTU_0 is the NTU when the number of the slit is 0 (Ns=0).

Next, pressure loss between fins without slits is shown by following equation[7].

$$\Delta Pb = 32/\mathrm{Re}_{fp} \times 1/(fp - tf) \times 1/2 \times g/g \times U^2 \quad (21)$$

where, γ is specific weight of air in standard temperature and pressure, g is gravity, Re_{fp} is shown by following equation.

$$\mathrm{Re}_{fp} = U \times \{2 \times (fp - tf)\}/n$$

On the other hand, pressure loss of a slit is shown by following equation.

$$\Delta Ps = 2 \times 1.328/\mathrm{Re}_a^{0.5}$$
$$\times 1/(fp - tf) \times 1/2 \times g/g \times U^2 \quad (22)$$

And total pressure loss is shown by following equation.

$$\Delta P = \left\{ \begin{array}{l} (Lp - Ns \times Ws) \times 32/\mathrm{Re}_{fp} \times 1/(fp - tf) \\ + Ns \times Ws \times 2.656/\mathrm{Re}_a^{0.5} \times 1/(fp - tf) \end{array} \right\}$$
$$\times 1/2 \times g/g \times U^2 \quad (23)$$
$$= Lp \times \Delta Pb + Ns \times Ws \times (\Delta Ps - \Delta Pb)$$

Therefore, the rate of the pressure loss increased by the number of the slit is shown by following equation.

$$\Delta P^* = (Ns \times Ws/Lp) \times (\Delta Ps/\Delta Pb - 1)$$
$$= (N \times Ws/Lp)$$
$$\times \{(2.656/\mathrm{Re}_a^{0.5})/(32/\mathrm{Re}_{fp}) - 1\} \quad (24)$$
$$= (N \times Ws/Lp)$$
$$\times [0.083 \times \{2 \times (fp - tf)/(Ws/U \times n)^{0.5} - 1\}]$$

The range of slit width (Ws) shown by equation (11) is substituted for the equation (24).

$$\Delta P^* = Ns \times (424 \times U \times (fp - tf)^2 / Lp) \quad (25)$$

The pressure loss is increased with increasing of the number of slit (Ns) proportionally.

Generally the slits are designed so that the rate of the heat transfer amount which is increased by the number of the slit shown in equation (20) may exceed the rate of the pressure loss which is increased by the number of the slit shown in equation (25).

4.1 Performance in heat transfer

Comparison of pattern in the heat transfer amount gotten by CFD which forms by each slit of a conventional slit and an optimized slit is shown in figure 13. The slits named 4 from 1 exist in the 1st low of pipe, and another slits exist in the second low of pipe.

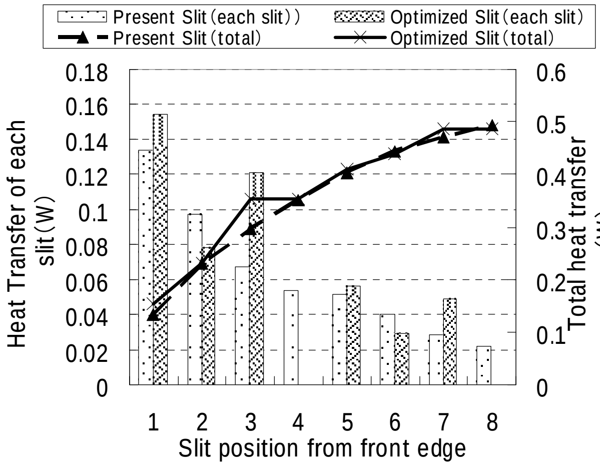
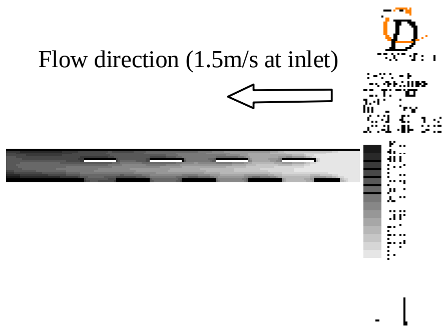


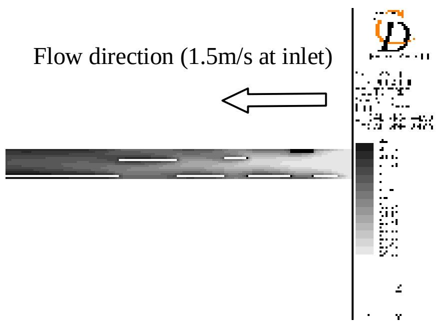
Fig.13 Trend of heat transfer made by each slit.

As it was above-mentioned, when air goes to a downstream side, the temperature of air will be close to the temperature of fin surface, and the heat transfer amounts of slit become a constant value. On the other hand, the heat amount of the 3rd slit exceeds the heat amount of the 2nd slit, and the optimized slit is different from a conventional slit in the pattern of the heat transfer.

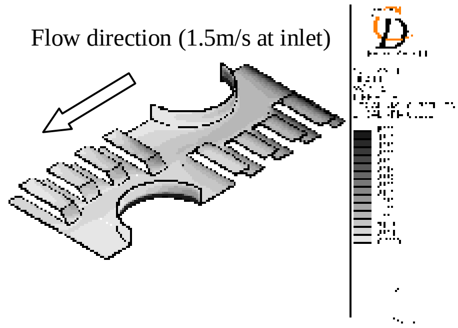
To consider the details of heat transfer phenomenon, the air temperature distribution at the fin central plane and heat flux distribution on the fin surface of a conventional slit and an optimized slit are shown in figure 14.



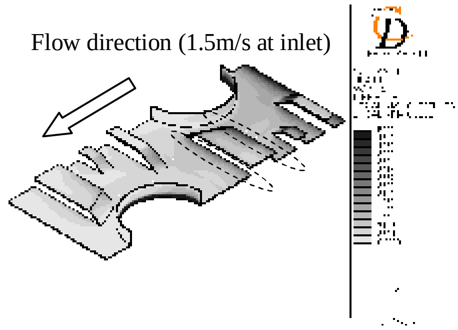
(a) Temperature contour of air (conventional slit).



(b) Temperature contour of air (optimized slit).



(c) Heat flux contour on fin surface (conventional slit).



(d) Heat Flux contour on fin surface (optimized slit).

Fig.14 Characteristics of heat transfer for each fin.

In conventional fin, all slits except 1st one undergoes influence of a temperature boundary layer in the upstream side one. On the other hand, in optimized fin, a temperature boundary layer of all slits is renewed. In the slit which is the 3rd from a edge of the optimized slit in particular, improvement of heat transfer performance by the edge effect also exists at the fin base part, not only updraft section of a slit. The improvement effect of heat transfer like the slit is obtained in the fin base part on the slipstream side of the 3rd slit. The reason why the performance of the optimized slit improved is based on this heat transfer pattern.

4.2 Performance in pressure loss

Comparison in the pressure loss gotten by CFD which forms by each slit of a conventional slit and an optimized slit is shown in figure 15.

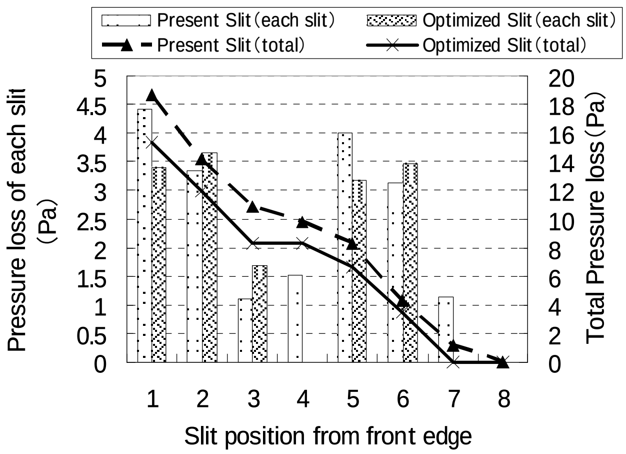
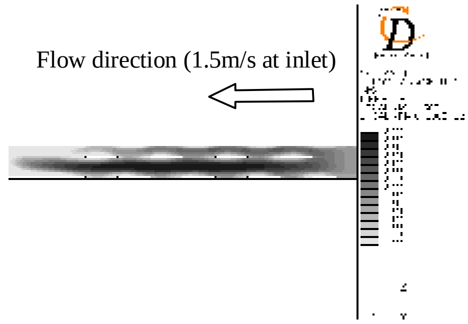


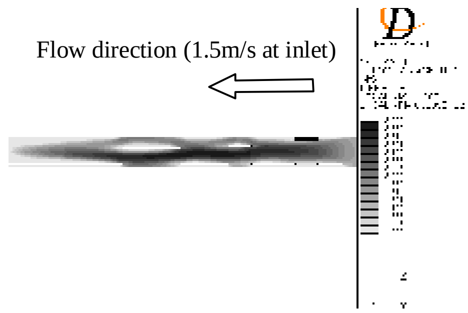
Fig.15 Trend of pressure loss made by each slit.

The optimized slit is almost same with a conventional slit in the pattern of the pressure loss. So, the number of the slit has caused the difference in the total pressure loss performance.

To consider the details of pressure loss phenomenon, the air velocity distribution at the fin central plane of a conventional slit and an optimized slit are shown in figure 16.



(a) Velocity contour of air (conventional slit).



(b) Velocity contour of air (optimized slit).

Fig.16 Characteristics of pressure loss for each fin.

While maximum velocity between fins of a conventional slit is about 4.6 (m/s), maximum velocity between fins of an optimized slit is about 4.1 (m/s). An overall flow of an optimized slit is uniform than a conventional slit. And air flow becomes uniform because the 3rd slit from edge is wide, and the fin base part on the slipstream side of the slit is the flow structure like the slit part as it was above-mentioned.

The optimized slit is different from a concept of conventional slits in a relation between the number of the slit and the heat transfer amount, and pressure loss.

5. Conclusion

The new technique of the optimization, especially for heat and fluid problems which has a complicated design area of solution that consists of many design variables, is proposed. The proposed method was applied to the development of the heat exchanger fin, and the result verifying the validity is reported. And an optimized slit get the following result.

(1) About the element unit of heat exchanger, an optimized slit is improved about 10 % (dry condition) and 25% (wet condition) more than a conventional slit in pressure loss with same heat amount.

(2) About the case which is mounted on a product, an optimized slit is improved about 7% (SH09APG) and 15% (SH12AS4) more than a conventional slit in flow rate

This proposed method, which divides complicated design area of solution into the several design areas, can be acquired each pareto which have different feature rationally. And optimization in the respective hierarchies becomes possible by dividing into the domains according to the priority of the target function. It enables to get the optimum solution and to build a significant data base.

Therefore, this proposed method is a very effective method in an actual development.

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