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Study on characteristics of heat transfer enhancement of straight-line fin row in packaged heater of natural blast hot water boiler

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Abstract
In this paper, we analyzed the heat transfer from high temperature combustion gas generated by coal combustion in a fixed bed boiler with heat output of 120 kW to a hot water heater through a longitudinal blade.
Moreover, from the analysis results, a reasonable structural parameter of the hot water heater was determined and introduced into the production, which saved 135 tons of coal per year, reducing the metal consumption by 12% compared to the previous one under the condition of the same heat output.

Keywords: Fixed bed boiler, hot water heater, longitudinal blade, cascade, thermal efficiency, heat transfer surface

Introduction
Heat transfer surfaces with arrays of blades are widely applied in engineering practices such as cooling heat exchangers or electronic devices.
These heat transfer surfaces are designed to enhance heat transfer through an additionally installed heat transfer surface.
Heat transfer is a research area of thermal engineering that deals with the generation, consumption, conservation and exchange of thermal energy between physical systems.
The thermal energy is transferred from one system to another by several methods: heat conduction, heat convection and thermal radiation.
Each heat transfer mechanism has its unique characteristics and is represented by characteristic equations.
We experience several phenomena of heat transfer in everyday life.
Heat transfer is a very inclusive field, and mathematical studies on each mechanism are being carried out because of its characteristics, among which the popular research subject with worldwide focus is the heat transfer through the cascade.
In addition to traditional applications such as internal combustion engines, compressors and heat exchangers, the heat transfer interface with a cascade of blades is widely applied for cooling spacecraft and electronic devices.
Kraus [1] conducted a comprehensive survey of blade technology for over 60 years and reported the results.
The optimization of the blade is very important because when installing the blade, the mass and volume of the device increases and the production cost increases.
Yeh etc. [1] theoretically investigated the optimal spacing of longitudinal blades in forced convection and used rectangular, convex, triangular and concave parabolic blades for analysis.
Senol [3] and Mobedi [4] also performed a three-dimensional heat transfer analysis through a vertical rectangular blade to provide the basis for determining the reasonable geometry.
On the other hand, Arslanturk [5] introduced the first-order heat analysis and optimization of annular blades with constant cross-section.
Mueller and abu-muulauch [6] experimentally determined the temperature distribution for the blades cooled by natural convection and radiation and compared the measured data with the results of the modeling. The above studies showed that the heat transfer by radiation was 15-20% of the total amount.

Therefore, it can be seen that the optimization of the blade has a significant effect on the thermal radiation.

In the previous studies, the temperature distribution and blade efficiency according to the blade length were analyzed numerically.

Malekzadeh [7, 10] introduced a differential element method to maximize the heat transfer rate for any volume of the blade under the influence of convection and radiation.

Dharma etc. [8] studied the heat transfer in a horizontally arranged cascade subjected to natural convection and radiation.

Kobus and Cavanaugh [9] described a theoretical model to propose the optimal profile of pin-shaped blades that consume the least material for various convective heat transfer coefficients.

Li etc. [11] also evaluated the cooling performance with the structural parameters of heat sink for cold cooling of thermoelectric generators and Reynolds number of the flow through experiments and obtained the geometry with minimum thermal resistance of the heat sink.

An analysis of the performance and optimization of a radiating fin whose thickness varies step by step was also proposed by Arslanturk [12].

Azarkish etc. [13] studied the geometry optimization of longitudinal blades with volumetric heat generation to maximize heat release for a given blade volume.

Govinda [14] analyzed the heat transfer from a vertically aligned cascade by laminar natural convection and radiation in a three-dimensional approach.

In the studies to obtain the temperature profile of the blade, the homotopy perturbation method was used, and recently Cuce etc. [15] introduced an analytical expression for the blade effect using the homotopy perturbation method to evaluate the performance of the convective straight blade.

Mert etc. [16] carried out a mathematical analysis for the enhancement of natural convection-radiation heat transfer of straight blades with step change.

Chandra [17] designed a structure of a heat sink for electronic cooling and performed heat transfer performance analysis using a tool for thermal analysis.

In addition, it can be seen that the study to enhance heat transfer through the heat sink is widely conducted worldwide and its reasonable geometry is different according to the specific conditions of each case.

Heat transfer enhancement of the heat transfer surface using a cascade has been widely applied in engineering applications, in many cases for heat release into the surrounding medium.

In order to enhance the heat transfer in the heat exchanger, it is necessary to increase the heat transfer coefficient for small side.

To this end, by changing the flow pattern of the medium, we can increase the flow velocity near the heating surface and install a cascade of blades, preventing the flow of the medium from affecting.

In this case, the cascade is not applied to heat release but to absorb more heat.

Barma etc. [18] improved the generator output by applying a cascade to enhance heat transfer through the hot side as well as cooling of the cold side in a thermoelectric generator producing electricity from the waste heat of the oil heater.

That is, to determine the rational structural parameters of the air supplied to the oil heater and the radiator (heatsink) located in the flue gas channel of the biomass fuel to maximize the power of the thermoelectric generator, the accuracy was verified through the experiment, and the reasonable structural parameters of the cascade where the power of the thermoelectric generator is maximized were obtained.

Raul etc. [19] enhanced the heat transfer by placing a cascade of blades on the combustion gas side front of a lead pipe heater in a yellow sugar production process.

As a result, the heat transfer rate increased by 105% on the hot side where the cascade was placed, and the thermal efficiency of the whole sugar production process increased from 31.4% to 41.8%.

This suggests a good way to improve the efficiency and save fuel by modifying the equipment with small investments in small-scale thermal plants fueling fossil fuels or biomass.

In general, heating of production buildings and public buildings, including greenhouses or farms, located tens of kilometers away from the area where production and public buildings and population are concentrated, is unsuitable to connect to the central thermal network.

These buildings are equipped with their own heating equipment and provide winter heating, where a fixed-bed boiler is used to burn anthracite or lignite.

Fixed-bed boilers have the advantages of no power consumption in boiler operation, no high fuel quality requirement, and sufficient number of personnel needed for equipment management, but they have the disadvantages of low heat output per boiler and low thermal efficiency.

In order to improve the heat output and thermal efficiency per boiler of a fixed bed boiler, it is important to improve the heat transfer performance of the heater.

In this paper, we have determined the reasonable size of the conventional rectangular blade placed to improve the heat transfer performance of the heat transfer surface and the heat transfer efficiency of the heat transfer surface in a fixed bed boiler with a lead pipe heater.

The determination of reasonable dimensions was done by obtaining the geometry of the fin array when the heat transfer performance was maximized under the condition of gas flow channel or heat sink base (base) dimensions were determined.

The distinguishing point from previous studies in the rational geometry determination in this paper is that the acid-point temperature should be taken into account because the medium that brushes the fin is the combustion gas that is produced by combustion of coal, and therefore SOx and NOx present in the gas.

In addition, the aspects of manufacturing and construction should also be taken into account in determining the optimal size of the blade.

In this study, we have proposed a reasonable size of the cascade to enhance heat transfer when using the heater outer side wall, which was not used as the heat transfer surface in a natural blower boiler previously.

The analysis of this problem was carried out by computational fluid dynamics analysis.

In this study, we determined the size of the cascade where the combustion gas temperature after passing the heater was higher than the acid point and the maximum heat transfer performance was achieved under the defined root structure size where the cascade was placed.

2. Mathematical model of heat transfer surface with cascade of blades

2.1 Mathematical model

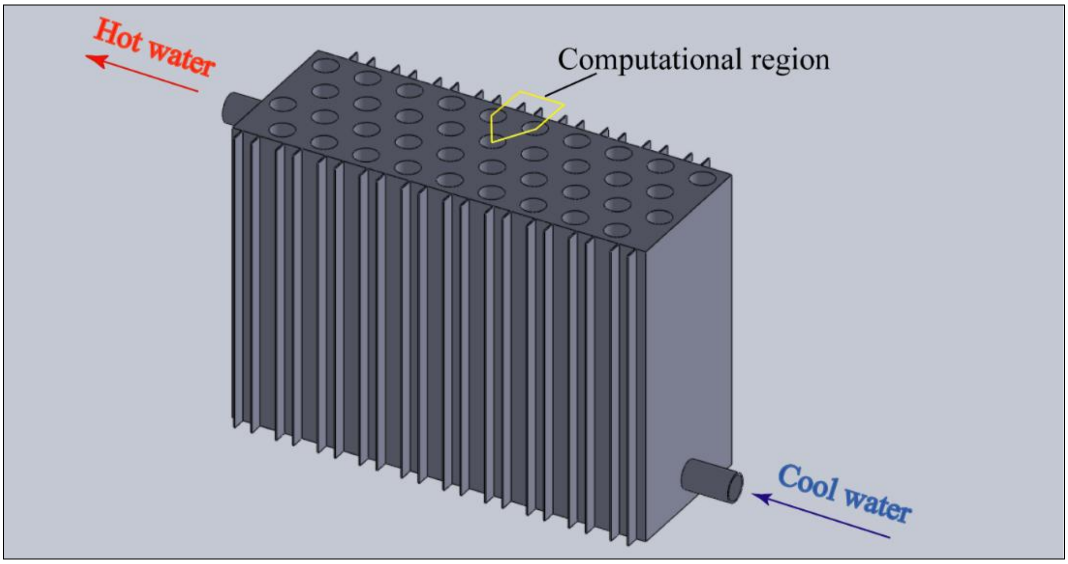
Since the buoyancy of gas is upward, the gas flow due to the buoyancy of high temperature combustion gas heated by the heat of combustion of coal in a natural blower boiler is also upward.

Therefore, a structure with the smallest flow resistance received by the gas flow by the cascade must be constructed.

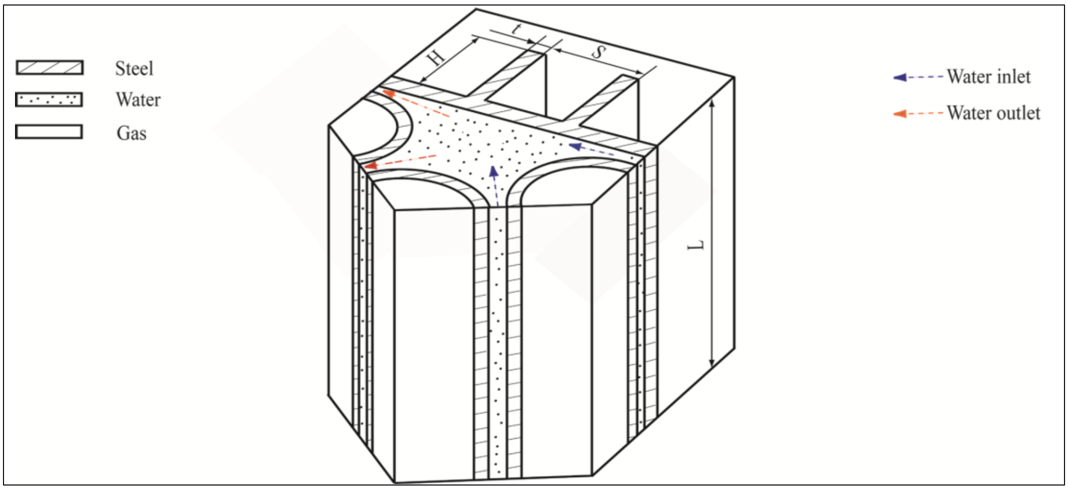
Therefore, we apply a longitudinal arrangement of blades along the gas flow.

The computational domain for the heat transfer surface with a cascade of blades is chosen as the part where the gas flow rate and temperature distribution are considered to be symmetrical.

The geometry of the cascade used in the numerical calculation is shown in Figure 1.



a. Geometrical model of the heat transfer surface with a cascade arrangement.



b. Computational domain

Fig 1: Geometric model and computational domain of the heat transfer surface with a cascade of blades

2.2. Basic equations

The temperature field and velocity field in the computational domain should satisfy the mass conservation equation, momentum conservation equation and energy conservation equation.

The three-dimensional heat conduction equation in the cascade is also given.

In our calculations, the characteristics of the fluid and the blade material are considered to be constant.

In this paper, the flow of fluid is analyzed as three dimensional, steady and incompressible fluid.

Continuity equation for fluid

$$\frac{\partial \omega_x}{\partial x}+\frac{\partial \omega_y}{\partial y}+\frac{\partial \omega_z}{\partial z}=0 \qquad (1)$$

Equation of motion for fluid

$$\frac{\partial(\omega_x\omega_x)}{\partial x}+\frac{\partial(\omega_x\omega_y)}{\partial y}+\frac{\partial(\omega_x\omega_z)}{\partial z}=$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2\omega_x}{\partial x^2}+\frac{\partial^2\omega_y}{\partial y^2}+\frac{\partial^2\omega_z}{\partial z^2}\right)+\frac{\nu}{3}\frac{\partial}{\partial x}\left(\frac{\partial^2\omega_x}{\partial x^2}+\frac{\partial^2\omega_y}{\partial y^2}+\frac{\partial^2\omega_z}{\partial z^2}\right)$$

$$\frac{\partial(\omega_x\omega_y)}{\partial x}+\frac{\partial(\omega_y\omega_y)}{\partial y}+\frac{\partial(\omega_y\omega_z)}{\partial z}= \tag{2}$$
$$-\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2\omega_x}{\partial x^2}+\frac{\partial^2\omega_y}{\partial y^2}+\frac{\partial^2\omega_z}{\partial z^2}\right)+\frac{\nu}{3}\frac{\partial}{\partial y}\left(\frac{\partial^2\omega_x}{\partial x^2}+\frac{\partial^2\omega_y}{\partial y^2}+\frac{\partial^2\omega_z}{\partial z^2}\right)$$

$$\frac{\partial(\omega_x\omega_z)}{\partial x}+\frac{\partial(\omega_y\omega_z)}{\partial y}+\frac{\partial(\omega_z\omega_z)}{\partial z}=$$
$$-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2\omega_x}{\partial x^2}+\frac{\partial^2\omega_y}{\partial y^2}+\frac{\partial^2\omega_z}{\partial z^2}\right)+\frac{\nu}{3}\frac{\partial}{\partial z}\left(\frac{\partial^2\omega_x}{\partial x^2}+\frac{\partial^2\omega_y}{\partial y^2}+\frac{\partial^2\omega_z}{\partial z^2}\right)$$

Energy equation

Energy equation for gas

$$\frac{\partial(\omega_xT_g)}{\partial x}+\frac{\partial(\omega_yT_g)}{\partial y}+\frac{\partial(\omega_zT_g)}{\partial z}=a_g\left(\frac{\partial^2T_g}{\partial x^2}+\frac{\partial^2T_g}{\partial y^2}+\frac{\partial^2T_g}{\partial z^2}\right)+S \tag{3}$$

Energy equation for gas

$$\omega_x\frac{\partial T_w}{\partial x}+\omega_y\frac{\partial T_w}{\partial y}+\omega_z\frac{\partial T_w}{\partial z}=a_f\left(\frac{\partial^2T_w}{\partial x^2}+\frac{\partial^2T_w}{\partial y^2}+\frac{\partial^2T_w}{\partial z^2}\right) \tag{4}$$

Energy equation for solid

$$a_s\left(\frac{\partial^2T_s}{\partial x^2}+\frac{\partial^2T_s}{\partial y^2}+\frac{\partial^2T_s}{\partial z^2}\right)=0 \tag{5}$$

The heat transfer mechanism from combustion gas to cascade is the forced convection heat transfer and radiation heat transfer.

For radiation heat transfer analysis, the Discrete Ordines model was used.

$$\nabla\cdot\left(I(\vec{r},\vec{s})\vec{s}\right)+(\alpha+\sigma_s)I(\vec{r},\vec{s})=\alpha n^2\frac{\sigma T^4}{\pi}$$

$$+\frac{\sigma_s}{4\pi}\int_0^{4\pi}I(\vec{r},\vec{s})\Phi(\vec{s}\cdot\vec{s}')d\Omega' \tag{6}$$

2.3. Boundary condition

Region	Boundary condition
Gas inlet	u_g=0.3m/s T_g=653K (Based on the measured data)
Water inlet	u_{wt}=0.01m/s T_{wt}=353K
Gas outlet	p=101325Pa (1atm)
Water outlet	p=101325Pa (1atm)
Interface (gas-wall)	u_g=0m/s ε_w=0.94(steel with oxide layer)
Interface (water-wall)	u_{wt}=0m/s ε_w=0

2.4. Numerical calculation

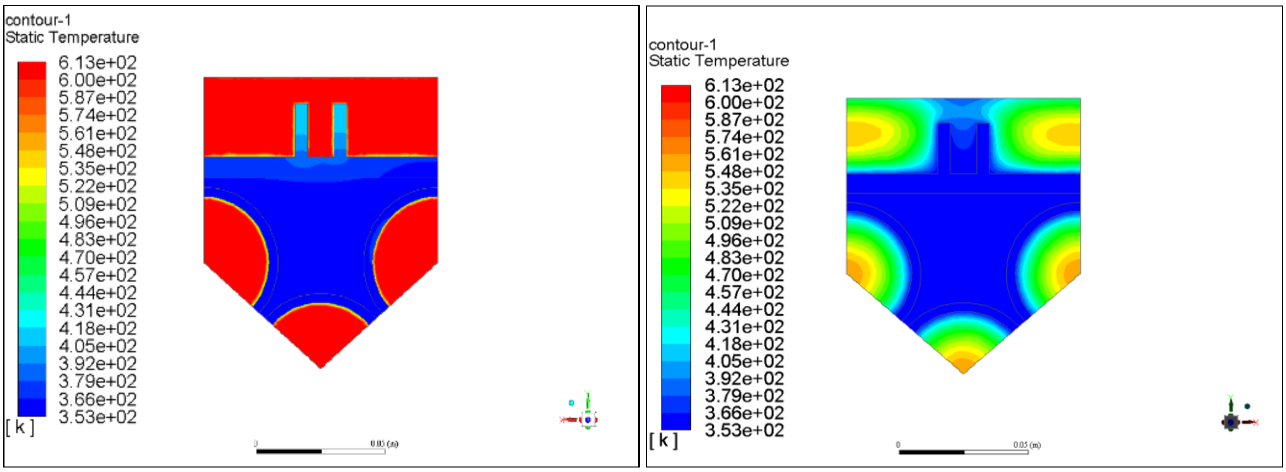
We analyzed the effect of blade geometry on heat transfer performance based on carrying out the numerical calculation by varying blade thickness by 2, 3, 4, 5, 6 mm, blade spacing by 25, 30, 40, 50, 60, 70, 80, 90 mm, and blade height by 20, 30, 40, 50 and 60 mm, respectively.

In this study, the calculation was carried out using the SIMPLE algorithm using the Thermo Fluid Flow Analysis software ANSYS Fluent 18.1.

Convergence estimations for mass, velocity components and energy are based on several error bounds: 10^{-4} for continuity equations, 10^{-7} for momentum equations and energy equations.

To verify the accuracy of the numerical calculations, first numerical calculations were performed by varying the blade spacing between 25mm, 30, 50mm and 100mm for a blade height of 10mm and a blade thickness of 5mm, and the gas temperature was measured using a K-type thermocouple and compared with the calculated results.

Numerical results for mathematical model validation are shown in Figure 2.



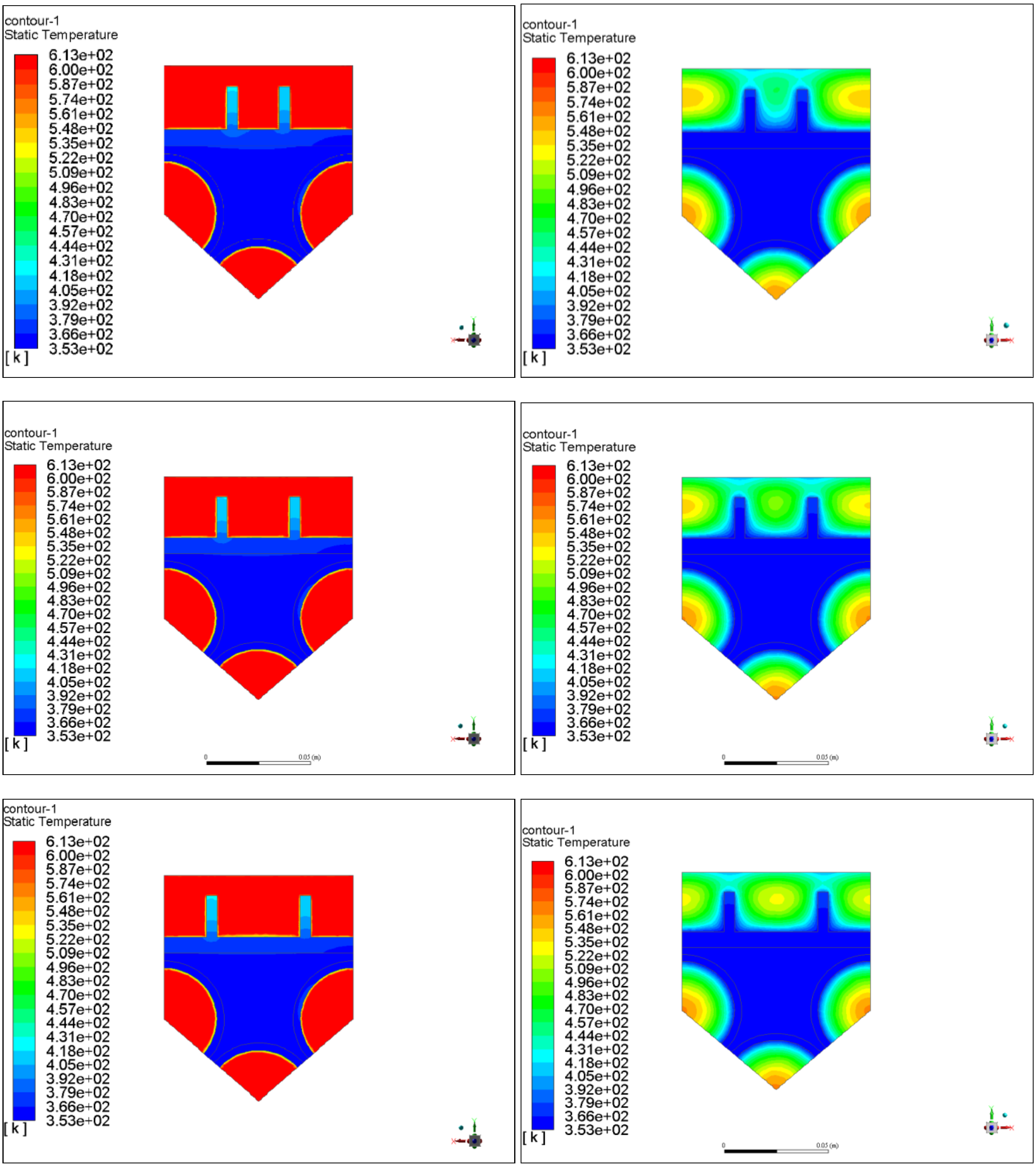


Fig 2: Temperature distribution at the gas inlet and outlet section along the blade spacing.

The thermocouple and monitor used for temperature measurement for the verification of mathematical model are shown in Fig. 3, and the code of the temperature monitor is SHIMADEN.

Fi 9g 3: Thermocouple and digital temperature controller used for measurement.

The location of temperature measurement point was fixed as the intersection of the end line of the blade and the bisector of the distance between the two blades in the gas outlet section.

The comparison results are shown in Fig. 4 and the maximum error is 1.9%.

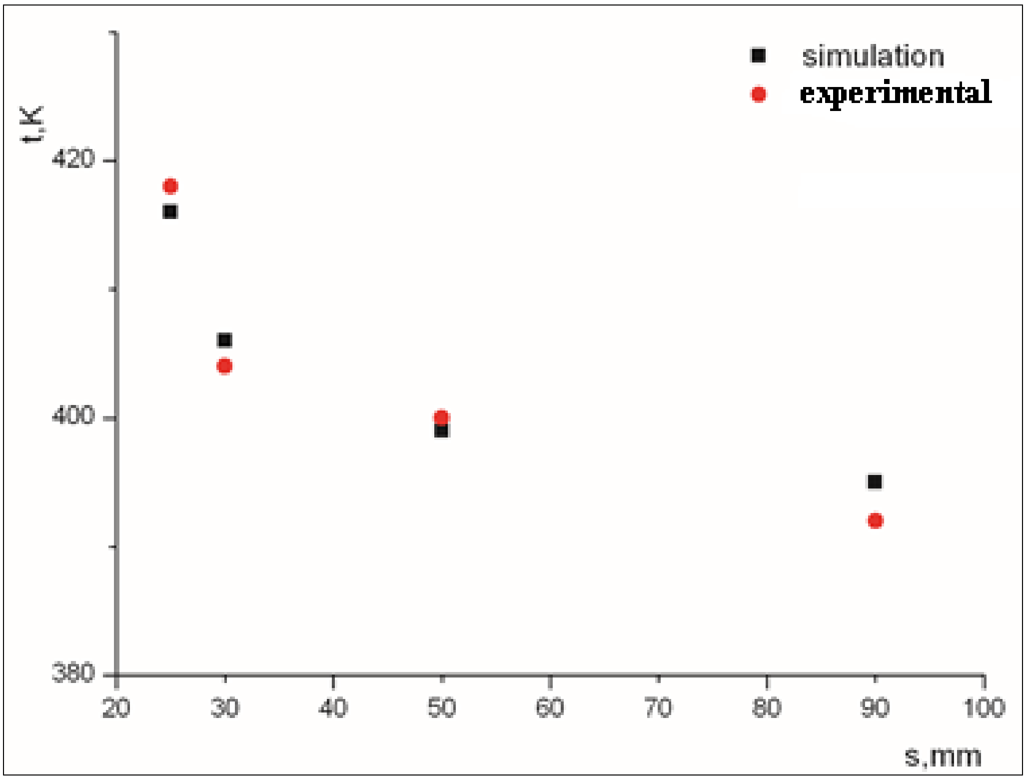


Fig 4: Simulation results and measurement results with varying blade-to-blade distance.

From the measured results, the calculation results with the geometrical and mathematical models developed above are considered reliable, and the heat transfer performance of the heat transfer surface with varying blade spacing, thickness and blade height is analyzed.

3. Results and Discussion

The calculation results for the blade spacing, blade thickness and height of the blade row are as follows:

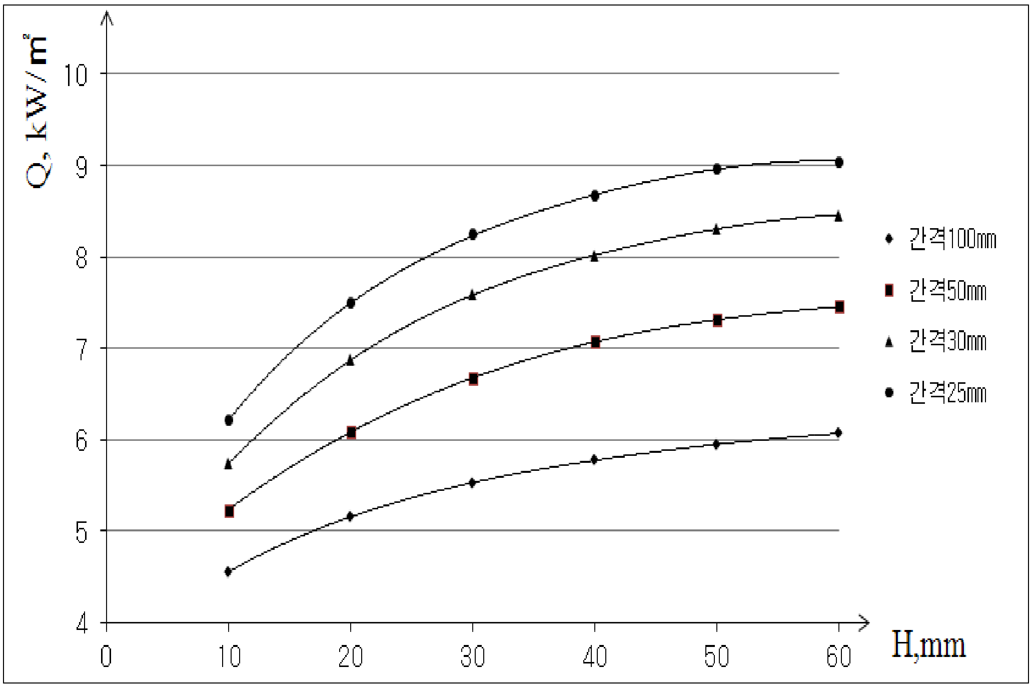


Fig 5: Heat absorption of the heat transfer surface along the blade height.

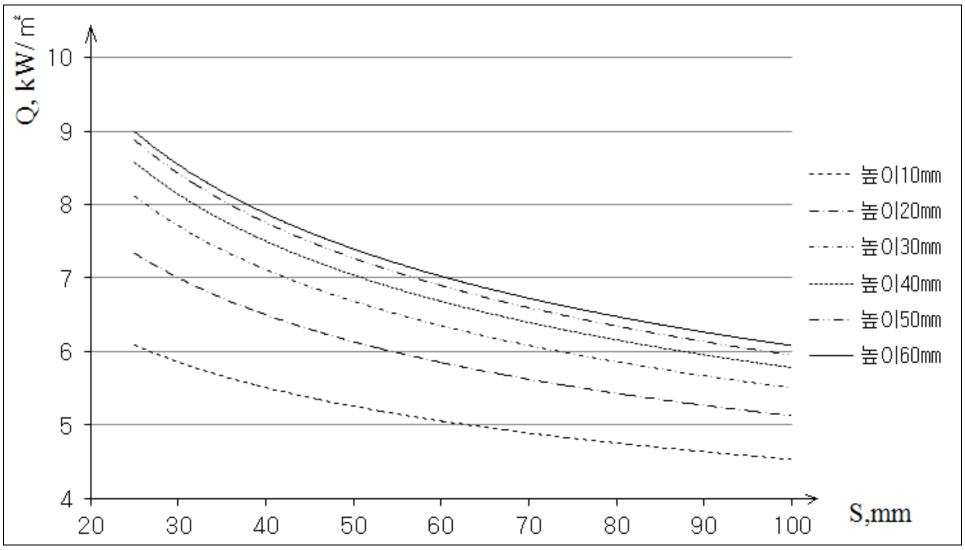


Fig 6: Heat absorption of the heat transfer surface with blade spacing.

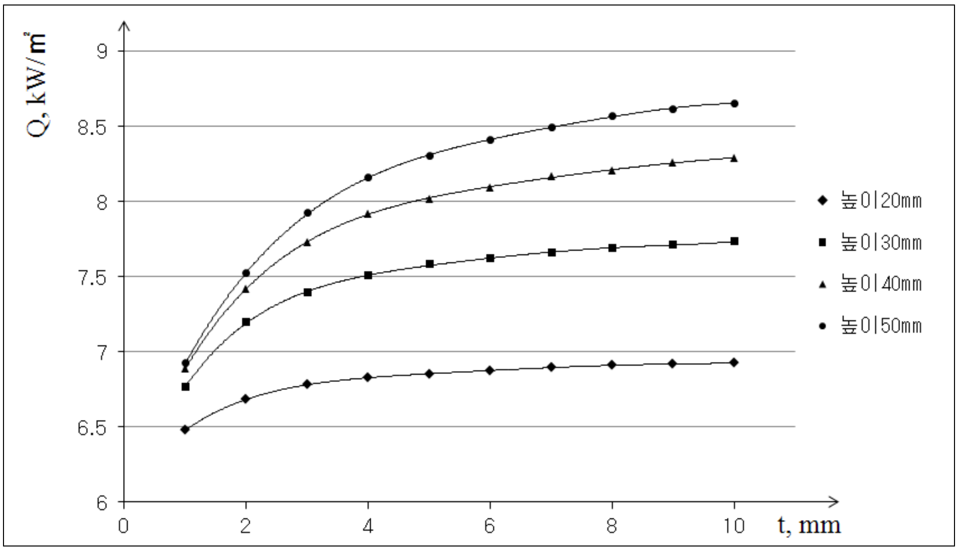


Fig 7: Heat absorption of the heat transfer surface with blade thickness.

Fig. 5 shows that the heat absorption through the heat transfer surface increases with increasing blade height.
It is also shown that the increase in heat absorption through the heat transfer surface decreases when the blade height is more than 60 mm.
Fig. 6 shows the heat absorption through the heating surface when the blade spacing varies from 25 to 100 mm.
Fig. 7 shows the heat absorption capacity of the heat transfer surface under constant remaining geometrical dimensions when the blade thickness varies from 1 to 10 mm.
Since the heat output of the heater depends on the number of heaters as well as on the geometry of the cascade, the number of heaters that influences the total heat output of heaters, the number of heaters, the height of heaters, the interblade spacing, and the blade thickness were determined so as to minimize the metal consumption using genetic algorithm.
Considering the composition and working characteristics of the fuel used in a 120 kW fixed-bed combustion boiler, it was newly obtained through the study that the optimum geometrical parameters by applying the Taguchi method were determined: the height of the cascade was 30 mm, the blade thickness was 5 mm, the blade spacing was 30 mm, the heater number was 3 and the heater height was 600 mm, and the maximum heat absorption in the whole heating system was higher than the acid degradation point.
A 120 kW heater with the geometry obtained through the study is shown in Figure 5.

Fig 8: Heater for improvement of heat transfer performance

The calculation results are significant basic data in the design of a packed vertical pipe heater.
The draft tube for the fabrication of the new heater is saved

by 25% compared to the conventional single-tube heat pipe heater under the same condition of 120 kW heat output

Conclusion

The introduction of a new heater could result in reducing the coal consumption from the conventional 250 kg per day to a minimum of 160 kg per day under the same conditions as 120 kW of heat output.

Of course, the new type of heater is manufactured, which consumes additional materials in the manufacture of the cascade, but is compensated in a short period due to the benefits obtained.

In the temperate zones of the northern hemisphere, heating should be provided for at least 150 days from autumn to early spring every year.

The amount of coal saved per day in a heater is not much, but when 10 heaters operate 150 days in a year, the amount of fuel saved reaches 135 tons and 1350 tons of coal is saved for 10 years.

The aim of this study was to obtain a reasonable heater's structural parameter to increase the thermal efficiency of a 120 kW coal-fired fixed-bed boiler used for heating a local building far away from the central heating system and without significant heating demand.

The results of the research introduction show that the thermal efficiency is high and coal is saved compared to the previous one.

The heat exchange conditions of the heater such as fuel consumption, combustion gas quantity and boiler furnace size depend on the heat output of the heater.

In this study, we have determined a reasonable structural parameter of the cascade applied to improve the heat transfer performance in the case of the heater power of 120 kW.

However, it cannot be conclude that these structural parameters are reasonable in the case of different heat output.

We will further study to establish a reasonable structural parameter of hot water boiler heaters with several heat output.

Symbol

a_g, a_s -Coefficient of thermal diffusion in gas and solid, m²/s S -Terms generated by radiation heat transfer $\vec{r}$ -Position vector, m $\vec{s}$ -Direction vector, m $\vec{s}'$ -Scattering direction vector, m s -Path length, m n -Refractive index P-Fluid pressure, Pa	I -Radiation intensity relative to position and direction T_g-Temperature of fluid, K T_s-Temperature of solid, K T_w-Temperature of water, K u_g-Velocity of gas entering inlet interface,m/s T_g-Gas temperature at inlet interface, K u_{wt}-Velocity of water entering the inlet interface, m/s T_{wt}-Water temperature at inlet interface, K

Greek letters

α -Absorption coefficient $\omega_x, \omega_y, \omega_z$ -Coordinate direction velocity σ_s -Scattering coefficient ν -Kinematic viscosity, m²/s	σ -Stefan-Boltzmann constant $\left(5.672\times10^{-8}\mathrm{W/m^2\cdot K^4}\right)$ Ω' -Solid angle, Sr ε_w-degree of blackness of metal wall
α -Absorption coefficient ω_x, ω_y, ω_z -Coordinate direction velocity σ_s -Scattering coefficient ν -Kinematic viscosity, m²/s	σ -Stefan-Boltzmann constant $\left(5.672\times10^{-8}\mathrm{W/m^2\cdot K^4}\right)$ Ω' -Solid angle, Sr ε_w-degree of blackness of metal wall

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