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Uneven longitudinal pitch effect on tube bank heat transfer in cross flow

Dongkyun Lee [a,1], Joon Ahn [b,2], Seungwon Shin [c,*]

[a] Department of Mechanical Engineering, Hongik University, Seoul 121-791, Republic of Korea
[b] School of Mechanical Systems Engineering, Kookmin University, Seoul 136-702, Republic of Korea
[c] Department of Mechanical and System Design Engineering, Hongik University, Sangsu-dong, 72-1, Mapo-gu, Seoul 121-791, Republic of Korea

HIGHLIGHTS

► We performed numerical analysis for the optimal operation of HRSG system.
► Longitudinal pitch distance of the tube banks can be controlling factor.
► Increasing averaged longitudinal distance enhances the overall heat transfer.
► With uneven pitch ratio, individual heat transfer coefficients tend to oscillate.
► The general correlation for the individual Nusselt numbers was obtained.

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ABSTRACT

For the optimal operation of steam generation in the HRSG system, the longitudinal pitch distance of the tube banks can be controlled independently for each individual row. To achieve a uniform heat transfer rate for each row of the tube bank, we conducted a full numerical study that includes a variation of the longitudinal pitch for the in-line tube bank geometry. The overall heat transfer across the tube bundles was compared to the existing correlation; it showed good agreement within a Reynolds number range of 500–2000. It was found that the transverse pitch effect can be included in the form of the maximum Reynolds number at the minimum cross section, as in conventional heat transfer formulation. Increasing the longitudinal space for uniformly distributed cylinders enhances the overall heat transfer. An appropriate relationship was obtained as a function of the pitch ratio in each direction. Finally, a general correlation of the individual Nusselt number for each row was obtained by considering the additional effect from uneven longitudinal pitch distances. The proposed correlation could predict the temperature variation across each row of the target HRSG system and was in agreement with the experimental results.

1. Introduction

The sharp increase in fossil fuel consumption from modernization and civilization has produced large amounts of greenhouse gases, especially CO_2. These greenhouse gases are believed to accelerate global warming; thus, many countries attempt to limit the amount of greenhouse gases released by enforcing laws. Because of legislative constraints, the search for alternative clean energy sources such as solar, geothermal heat, and wind power has become important. These renewable energy sources are effective in reducing greenhouse gas emission, but they still have obstacles in generating sufficient energy for overall consumption due to a limited energy transformation efficiency. However, recycling the redundant energy of an existing system to increase the performance is an indirect way of reducing greenhouse gases.

A combined heat and power plant (CHP) is one of the most widely used recycling energy systems in industrial facilities because it considerably improves the energy efficiency by reusing the waste heat from district heating [1,2]. Recently, a 1–10 MW small CHP system was constructed to be an emergency power source for large buildings such as hospitals, recreational buildings, or multipurpose buildings. Most hospitals and multipurpose buildings require not only hot water for space heating but also steam for sanitization purposes, so an additional heat recovery steam generator (HRSG) is necessary. An HRSG system can generate

* Corresponding author. Tel.: +82 2 320 3038; fax: +82 2 322 7003.
E-mail addresses: ldg0308@gmail.com (D. Lee), jahn@kookmin.ac.kr (J. Ahn), sshin@hongik.ac.kr (S. Shin).
[1] Tel.: +82 2 335 1633.
[2] Tel.: +82 2 910 4833; fax: +82 2 910 4839.

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Nomenclature

A	surface area of circular cylinder [m^2]
A_{bare}	surface area of circular cylinder without fin [m^2]
A_{fin}	surface area of fin [m^2]
c_p	specific heat [J/kg K]
D	diameter of circular cylinder [m]
h	overall convective heat transfer coefficient [W/m^2 K]
h_{bare}	convective heat transfer coefficient of circular cylinder without fin [W/m^2 K]
k	thermal conductivity [W/m K]
$\dot{m}$	mass flow rate [kg/s]
Nu_D	overall Nusselt number for the entire tube bank
$Nu_{D,i}$	individual Nusselt number for ith row of the cylinder
Pr	Prandtl number
Δp	pressure drop [Pa]
Q	total heat transfer rate for the entire tube bank [W]
Q_i	individual heat transfer rate for ith row of the cylinder [W]
$Re_{D,max}$	maximum Reynolds number
S_L	longitudinal pitch [m]
$S_{L,1}$	upstream longitudinal pitch for ith row of the cylinder [m]
$S_{L,2}$	downstream longitudinal pitch for ith row of the cylinder [m]
$S_{L,Cylinder}$	distance between the cylinders [m]
$S_{L,Module}$	distance between the modules [m]
$\overline{S_L}$	averaged longitudinal pitch [m]
S_T	transverse pitch [m]
$T_{i,1}$	upstream bulk mean temperature for ith row of the cylinder [K]
$T_{i,2}$	downstream bulk mean temperature for ith row of the cylinder [K]
T_{in}	inlet temperature at the simulation domain [K]
T_{out}	outlet temperature at the simulation domain [K]
T_s	tube surface temperature [K]
ΔT_{LMTD}	log mean temperature difference [K]
U	total convective heat transfer coefficient including fin effect [W/m^2 K]
V_{max}	maximum velocity [m/s]

Greek symbols

η_{fin}	fin efficiency
μ	viscosity [N s/m^2]
ρ	density [kg/m^3]

large amounts of high temperature steam by using the waste heat from exhaust gas in the CHP system. Through the use of the HRSG system, the total energy efficiency can be significantly improved. Thus, overall CO_2 generation can be reduced by decreasing fossil fuel consumption.

A simplified schematic of the target HRSG system connected to a small engine-powered CHP is shown in Fig. 1. Hot exhaust gas from the engine exchanges its heat with water that runs inside the risers. The evaporated water in each riser forms steam bubbles. When the coagulated bubbles begin to rise, they occupy a significant portion of the riser. They then gather in a steam drum above the risers. In the steam drum, the pure vapor steam is separated from the water pool by the difference in densities, and the underlying saturated water is recirculated back to the riser entrance through downcomers. Thus, it is vital to maintain a consistent evaporation rate in all the risers to ensure continuous water recirculation. Excess steam generation can block the flow in the riser, resulting in poor system performance. To maintain consistent evaporation, all the risers must experience a uniform heat transfer rate.

As shown in Fig. 2, the risers in an HRSG system can be simplified as tube banks in a cross flow. Because of their excellent heat transfer performance, tube banks are utilized in various engineering industries. A substantial amount of experimental and numerical research has been conducted to predict the overall heat transfer rate or the pressure drop across the tube bundles. The maximum Reynolds number, $Re_{D,max}$, which is evaluated at the minimum cross-sectional area, is used to calculate the pressure drop and the overall heat transfer across the tube bundles in most tube bank problems. The transverse pitch, S_T (perpendicular to the flow direction, as shown in Fig. 2), is considered to be a significant design factor for tube banks. Using the Nusselt number (Nu_D) correlation for the cross flow over a single cylinder which is a function of the Reynolds and Prandtl numbers [3–7], Grimison [8] included the effect of the transverse pitch on the tube banks by multiplying Nu_D by the appropriate constant. $Re_{D,max}$ was used to generate the Nusselt number correlation. This correlation can be applied to the tube bank geometry over 10 rows for either staggered or in-line arrangements. Zhukauskas [9] proposed an Nu_D correlation for a wide range of $Re_{D,max}$. The friction coefficient was also provided; it was evaluated from $Re_{D,max}$ with a geometric correction factor. This correlation is generally accepted in industry to predict the tube bank heat transfer in cross flow. Zdravistch et al. [10] proposed a numerical method for calculating the tube bank heat transfer for laminar and turbulent flows using the Reynolds-averaged Navier–Stokes (RANS) equations. They found that a two-dimensional numerical simulation of the tube bank problem provides reasonably accurate results consistent with the three-dimensional cases. They also determined that a relatively fine grid resolution is required to predict the surface heat transfer correctly.

More advanced relationships with different positioning of two cylinders in a tandem arrangement was investigated numerically [11]. For this, a commercial software program, FLUENT, was used and full benchmarking tests were performed. The focus was on the identification of the local heat transfer characteristics for each cylinder. With sufficient longitudinal distance, the mean Nusselt number for the upstream cylinder was found to approach to the single cylinder correlation. The downstream cylinder has 80% of the value of the upstream cylinder. The detailed hydrodynamic and thermal assessments were made, but only two cylinders were placed in an external flow field with no interaction between the neighboring cylinders. Hausen [12] proposed a modified correlation of Grimison's [8], which accounts for the spacing ratio between the tubes. He included the layout factor for both the in-line and staggered arrangements. Khan et al. [13,14] determined a more elaborate correlation. They suggested a general correlation of the Nusselt number for a wide range of parameters, including the longitudinal pitch, transverse pitch, Reynolds number, and Prandtl number. The boundary integral approach was used to drive the analytic solution for the average heat transfer coefficient of the tube bank. They proposed a simplified model of the Nusselt number for both the in-line and staggered configurations of the tube bank. Their correlation was limited to the laminar flow to identify the overall heat transfer across the entire tube bank. Wilson and Bassiouny [15] predicted the overall pressure drop and heat transfer characteristics of the laminar and turbulent flow of air across the tube. They conducted numerical simulations with various