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Heat transfer characteristics of air cross-flow for in-line arrangement of spirally corrugated tube and smooth tube bundles

LU Guo-dong (陆国栋)[†1], ZHOU Qiang-tai (周强泰)[2], TIAN Mao-cheng (田茂诚)[3], CHENG Lin (程 林)[3], YU Xiao-li (俞小莉)[1]

([1]*School of Mechanical and Energy Engineering, Zhejiang University, Hangzhou 310027, China*)
([2]*Department of Power Engineering, Southeast University, Nanjing 210096, China*)
([3]*School of Energy and Power Engineering, Shandong University, Jinan 250061, China*)
[†]E-mail: lgd0039007@sohu.com

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Abstract: An experimental study on heat transfer and resistance coefficients of linearly arranged smooth and spirally corrugated tube bundles in cross-flow was performed. The heat transfer and resistance coefficients are presented in this paper with transverse and longitudinal tube-pitch and tube geometries taken into account. The experiment's results can provide technical guidelines for application to horizontal air preheater with arranged in-line spirally corrugated tube bundles, especially to the air preheater for CFBCBs (Circulating Fluidized Bed Combustion Boilers).

Key words: CFB, Air preheater, Spirally corrugated tube, Linearly arranged tube bundles, Cross-flow
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INTRODUCTION

CFB (Circulating Fluidized Bed) boiler is well known and one of the most mature technologies in the world, and therefore the most commercial clean coal combustion technology at present. It developed very fast since it was first put into commercial operation in the 1980's. In China a large number of 125~135 MW CFB boilers are put into operation every year. CFB boilers require primary air pressure of as high as 15000~20000 Pa for the fluidization of coal particles, so high air pressure is required for the air preheater, with large pressure difference between air and flue gas. Horizontal air preheaters of smooth tube bundles arranged in-line are used in most cases at present in China, but low efficiency in heat transfer, large volume and surface area are the worst characteristics. The space of the flue gas path at the back part of the CFB boiler is not enough to accommodate an in-line bare tube air preheater even for a 50 MW capacity unit. When the CFBCB (Circulating Fluidized Bed Combustion Boiler) units are developed into larger capacity unit, the problem of the limited space for the flue gas path will be more serious. Study on air preheater with enhanced heat transfer suitable for CFB boilers has practical value.

As spirally corrugated tube is characterized by high heat transfer, it is often used as the component of air preheater for boilers in electric power plants and in industries. Southeast University did much research on heat transfer in spirally corrugated tube and on cross flow of spirally corrugated tube bundles with staggered arrangement. But there are no reports on the cross-flow heat transfer characteristics of spirally corrugated tube bundles arranged in-line, so an experimental study (Lu, 2004) on heat transfer and resistance coefficients of arranged in-line spirally corrugated tube bundles for cross-flow was performed.

EXPERIMENTAL DETAILS

Test system

The test system was composed of wind tunnels with both cold air and heated air parts (Fig.1). Heat exchange occurs in the test section with heated air crossing-flow horizontal tube bundles arranged in-line and cold air flowing in tubes. The test system was covered with heat insulation material. The test section is shown in Fig.2, containing 10 rows of three tubes each and half tubes on the side walls. The test tubes are smooth and spirally corrugated, O. D. of 40 mm, thickness of 1.5 mm, length of 340 mm. The spirally corrugated tube's geometric parameters such as the spacing of corrugation p and the depth of corrugation h, are shown in Table 1.

Thermo-couples are placed at the inlet and outlet of the test section to measure the air temperature.

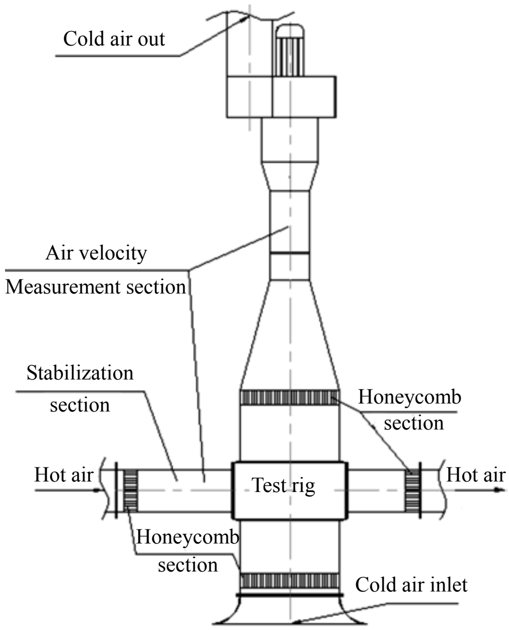

Fig.1 System diagram of the test rig

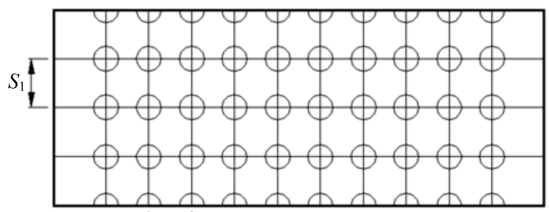

Fig.2 General view of testing cross section

Table 1 Geometric parameters of spirally corrugated tube

Tube serial number	p (mm)	h (mm)
A1	15	1.0
A7	16	1.25
A8	16	1.4
A3	20	1.0
A4	20	1.2
A9	20	1.4
A5	24	1.2
A2	24	1.5

Thermocouples are connected to FLUKE data acquisition system, providing junction compensation automatically for the thermo-couples at accuracy of 0.02 °C and frequency of 0.5 Hz. Before use, the thermo-couples were calibrated with thermostat oil bath and mercury thermometer. Inclined tube micromanometer with pure alcohol as medium was used for pressure difference measurement. All the experiments are performed under heated condition. Strict leakage tests were carried out before the experiments.

Test equipment and instrument

Tube bundles were arranged in-line, with transverse pitch of 60, 70 and 80 mm and longitudinal pitch of 50, 60 and 70 mm, respectively. Fifty-four groups of experimental studies for smooth and spirally corrugated tube were performed by orthogonal method with instruments listed in Table 2. Heated air velocity in the rectangular stabilization section was measured.

Table 2 Test equipment and instrument

Item	Model number and parameter
Steam boiler	Lss0.5-1.0-Y
FLUKE data acquisition system	DAQ26A, accuracy: 0.02 °C
Inclined tube micromanometer	YYT-200B
Mercury glass-stem thermometer	Accuracy: 0.1 °C
Pitot tube	Accuracy: ±(1.5~4.0)%

Hot air velocity was measured with 3 Pitot tubes (Fig.3). Cold air velocity was measured in a velocity measurement tube of 273 mm O. D. with a flute tube

(Fig.4) made of stainless steel tube of 10 mm O. D. and 1.5 mm thickness. The flute tube was calibrated before being put into use.

Two mercury thermometers with accuracy of 0.1 °C were placed one each at the inlet and outlet of the test section to measure the temperature. At the beginning of the experiments, the cold air system was operated first, then the heated air system. The heating system was composed of steam heating and electrical heating; a voltage regulator was used in the electrical heating system in order to maintain the heated air temperature fluctuation of ±1 °C. During the experiments, the cold air velocity was kept constant, with the heated air velocity being varied in order to obtain different heat transfer rate.

The test tubes and the tube plates were changed after each test.

Fig.3 Measurement of heated air with Pitot tube

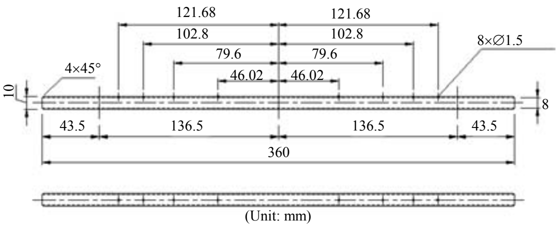

Fig.4 Measurement tube for cold air

TEST SYSTEM CHECKING AND DATA REDUCTION

Test system checking

The smooth tube was tested first. There are many heat transfer coefficient formulas for tube side, the formula by Dittus and Boelter (1930), and Kays and Crawford (1980) are used widely and the correlation equation of Kays and Crawford (1980) is considered as the most reliable one for gas especially for air, which is

$$Nu_{\mathrm{i}}=0.022Re_{\mathrm{i}}^{0.8}Pr_{\mathrm{i}}^{0.5} \tag{1}$$

Because the length of test tubes is short (only 340 mm long), a coefficient of correction for smooth tube is taken into account. The correction coefficient correlation equation given by Al-Arabi (1982) which is suitable for air is used here:

$$\overline{\varepsilon_1}=1+\frac{C}{x/D_{\mathrm{h}}} \tag{2}$$

where, $C=\frac{(x/D_{\mathrm{h}})^{0.1}}{Pr^{1/6}}\left(0.68+\frac{3000}{Re^{0.81}}\right)$.

The heat transfer efficient (dashed line in Fig.5) of smooth tube bundles arranged in-line can be written as:

$$Nu_{\mathrm{o}}=0.326Re_{\mathrm{o}}^{0.593}Pr_{\mathrm{o}}^{0.36}\left(\frac{s_1}{d_{\mathrm{o}}}\right)^{-0.18}\left(\frac{s_2}{d_{\mathrm{o}}}\right)^{0.34} \tag{3}$$

Eq.(3) is valid for $Re_{\mathrm{o}}=4.7\times10^3\sim9.6\times10^4$.

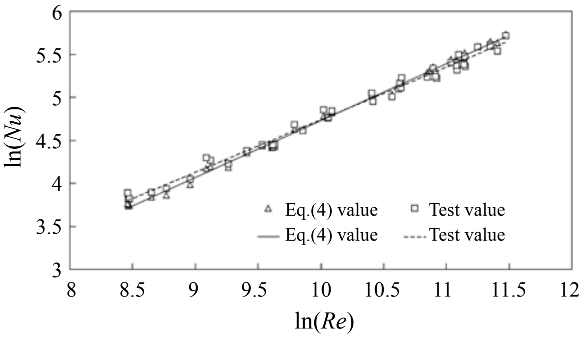

Fig.5 Comparison between correlation of heat transfer for smooth tube bundles arranged in-line and classical correlation equation

The experimental data agreed with that of Chen and Chen (1981):

$$Nu_{\mathrm{o}}=0.2\sqrt{\left(1+2\left(\frac{s_1}{d_{\mathrm{o}}}\right)-3\right)\left(1-\left(\frac{s_2}{d_{\mathrm{o}}}\right)\Big/2\right)^3}\,Re_{\mathrm{o}}^{0.65}Pr_{\mathrm{o}}^{0.33} \tag{4}$$

The subscript of "i" and "o" represents internal and external tubes respectively in Eq.(1)~Eq.(4). The characteristic temperature is the mean air temperature in internal and external tubes.

Comparison between the experimental data and Eq.(4) is shown in Fig.5, where the experimental data for tube side deviates by a maximum of 4.7% from Eq.(4), so the test system is reliable.

Mathematical model

Heated air:

$$Q_o=c_{po}[\rho_o V_o(n-1)s_1 l]\Delta t_o \tag{5}$$

where, Q_o is heat flux of heated air, kW; c_{po}, specific heat at constant pressure of the heated air, kg/(kJ·K); ρ_o, average density of the heated air in the test section, kg/m^3; V_o, the max speed of the heated air in the test section, m/s; n is the tube number in the test section, root; s_1, transverse pitch, mm; l is the clear length of tubes between the tube plates, mm; Δt_o, temperature difference of heated air in the test section, K.

Cold air:

$$Q_i=c_{pi}[\rho_i V_i n\pi d_i^2/4]\Delta t_i \tag{6}$$

where, Q_i, heat flux of cold air, kW; c_{pi}, heat at constant pressure of the cold air, kg/(kJ·K); ρ_i, average density of the cold air in the test section, kg/m^3; V_i, the max speed of the cold air in the test section, m/s; n is the tube number in the test section, root; d_i, inside tube diameter, mm; Δt_i, temperature difference of cold air in the test section, K.

The difference of heat flux between heated air and cold air is no more than 5% for most cases, and the average value of the heat flux of heated air and cold air is used as the total heat flux:

$$Q=(Q_o+Q_i)/2 \tag{7}$$

The total heat flux can be written as:

$$Q=KA\Delta t' \tag{8}$$

where, K is the total heat transfer coefficient without considering the thermo resistance of the tube,

$$K=\frac{1}{\bar{d}/\alpha_o d_o+\bar{d}/\alpha_i d_i} \tag{9}$$

where, α, heat convection coefficient, W/(m^2·K); $\bar{d}$, average value of inside and outside pipe diameter, mm; A is the average heat transfer area, m^2; $\Delta t'$, logarithmic average value of temperature inside and outside tube.

The heat transfer coefficient inside spirally corrugated tube is used from literature (Wang, 1995) and the heat convection coefficient of α_o for tube side can be obtained from Eq.(5)~Eq.(8). According to the analysis of dimension, the heat transfer coefficient of cross-flow spirally corrugated tube bundles arranged in-line can be written as:

$$Nu_o=aRe^b Pr^c\left(\frac{s_1}{d_o}\right)^d\left(\frac{s_2}{d_o}\right)^e\left(\frac{p}{h}\right)^f\left(\frac{h}{d_o}\right)^g \tag{10}$$

where, a~g are unknown parameters, determined by data regression.

The resistance coefficient can be obtained from Eq.(11)

$$Eu_o=\frac{1}{z}\frac{\Delta P_o}{\rho_o V_o^2/2} \tag{11}$$

where, ΔP_o, pressure difference in tube bundles, Pa; z is the number of tube rows.

According to the analysis of dimension, the Euler number can be written as:

$$Eu_o=aRe^b\left(\frac{s_1}{d_o}\right)^c\left(\frac{s_2}{d_o}\right)^d\left(\frac{p}{h}\right)^e\left(\frac{h}{d_o}\right)^f \tag{12}$$

where, a~f are unknown parameters, determined by data regression.

Comparison of heat transfer between spirally corrugated tube and smooth tube bundles arranged in-line

A comparison of K between spirally corrugated tube and smooth tube bundles arranged in-line is shown in Fig.6, and another comparison of Nu_o for tube side is shown in Fig.7. Fig.6 and Fig.7 show that the value of K of spirally corrugated tube bundles is 12.78%~41.5% higher than that of smooth tube bundles, and the value of Nu_o is 2.05%~17.02% higher correspondingly.

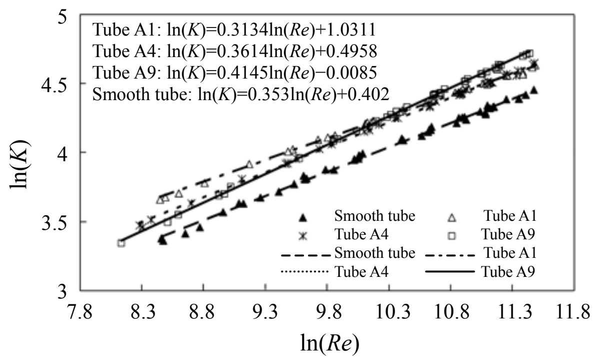

Fig.6 Comparison of total heat transfer coefficient between bundles of spirally corrugated tube and smooth tube arranged in-line

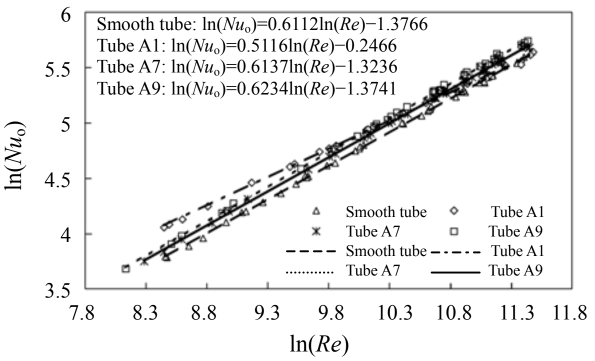

Fig.7 Comparison of heat transfer coefficient for tube side between bundles of spirally corrugated tube and smooth tube arranged in-line

Test result of smooth tube bundles

The test result of heat transfer coefficient is shown in Eq.(3). The friction coefficient obtained can be written as:

$$Eu_o = 0.7364 Re_o^{-0.021} \left(\frac{s_1}{d_o}\right)^{-2.15} \left(\frac{s_2}{d_o}\right)^{0.23} \quad (13)$$

Eq.(13) deviates by a maximum of 7.34% from the experiments data, which is in good agreement with the correlation equation by Zukauskas (1968) except for a little difference in some aspects, such as Eu_o decreases as Re_o increases when $Re_o \geq 10^4$, and Eu_o decreases as s_1 increases but increases as s_2 increases.

Test result of spirally corrugated tube bundles

The heat transfer coefficient inside the tube from Wang (1995) and the heat transfer coefficient for tube side can be written as:

$$Nu_o = 0.27 Re^{0.566} Pr^{0.36} \left(\frac{s_1}{d_o}\right)^{-0.26} \left(\frac{s_2}{d_o}\right)^{0.11} \left(\frac{p}{h}\right)^{0.04} \left(\frac{h}{d_o}\right)^{-0.16} \quad (14)$$

Eq.(14) is valid for $3.27\times10^3 \leq Re_o \leq 1.01\times10^5$, 15 mm$\leq p \leq$24 mm, 1.0 mm$\leq h \leq$1.5 mm, $1.5 \leq s_1/d_o \leq 2$, and $1.25 \leq s_2/d_o \leq 1.75$. Eq.(14) deviates by a maximum of 7.63% from the experiment's data.

The friction coefficient correlation equation for tube side can be written as:

When $9.59\times10^3 \leq Re_o \leq 1.01\times10^5$,

$$Eu_o = 0.855 Re^{-0.076} \left(\frac{s_1}{d_o}\right)^{-1.89} \left(\frac{s_2}{d_o}\right)^{0.16} \left(\frac{p}{h}\right)^{0.04} \left(\frac{h}{d_o}\right)^{-0.03} \quad (15)$$

Eq.(15) deviates by a maximum of 9.48% from the experiments data.

When $3.27\times10^3 \leq Re_o \leq 9.59\times10^5$,

$$Eu_o = 0.14 Re^{-0.25} \left(\frac{s_1}{d_o}\right)^{-1.03} \left(\frac{s_2}{d_o}\right)^{0.23} \left(\frac{p}{h}\right)^{0.42} \left(\frac{h}{d_o}\right)^{-0.36} \quad (16)$$

Eq.(16) deviates by a maximum of 7.65% from the experiments data. Eqs.(15) and (16) are valid for $1.5 \leq s_1/d_o \leq 2$, $1.25 \leq s_2/d_o \leq 1.75$, 15 mm$\leq p \leq$24 mm, and 1.0 mm$\leq h \leq$1.5 mm.

CONCLUSION

The study results can be summarized as:

1. The coefficient K of spirally corrugated tube bundles arranged in-line is higher than that of the smooth tube, by 10.55%~36.33%; the coefficient Nu_o for tube side is higher by 3.05%~33.4% respectively.

2. The heat transfer coefficient of air cross-flow of spirally corrugated tube bundles arranged in-line can be obtained from Eq.(14).

3. The friction coefficient of air cross-flow spirally corrugated tube bundles arranged in-line can be obtained from Eq.(15) and Eq.(16).

The results above can provide technical guideline for application to horizontal air preheater with spirally corrugated tube bundles arranged in-line, especially for CFBCB, and is also useful for superheater, reheater and economizer at the end part of the boiler.

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