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The effect of noncondensable gas on heat transfer in the preheater of the sewage sludge drying system

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Abstract−We used a shell-and-tube type preheater to investigate the effect of noncondensable gas on heat transfer. In the preheater of the drying system, heat is exchanged between steam-air mixed gas which is dryer outlet gas and sewage sludge. To evaluate the performances of the preheater, water was first used in the tube-side material instead of sewage sludge and steam-air mixed gas in the shell-side material. The test variables were as follows: mixed gas inlet temperatures range from 95 to 120 °C; inlet air content, m_{air}/m_{steam} from 55 to 83%; tube-side water flow rate from 42 to 62 kg/h. The shell-side heat transfer coefficient varied from 150 to 550 W/m^{2}K, which corresponds to the amount of noncondensable gas in the steam-air mixed gas and the overall heat transfer coefficient varied from 60 to 210 W/m^{2}K. Using sewage sludge as a tube-side material the overall heat transfer coefficient varied from 60 to 130 W/m^{2}K and the outlet temperature of sewage sludge was above 90 °C, which is high enough for reducing energy consumption in the dryer by preheating the sewage sludge.

Key words: Drying System, Preheater, Heat Transfer, Condensation, Noncondensable

INTRODUCTION

In current drying systems, energy consumption is about 1.3-1.5 times compared with the necessary energy to evaporate moisture contained in the sewage sludge. Air is generally used as a carrier gas in the dryer, so the dryer outlet gas contains noncondensable gas. When the dry outlet gas is used in the preheater as heating medium of raw sewage sludge ahead of the dryer, the energy consumption in the drying system can be reduced. Jin et al. [1] registered a Korean Patent which includes low-energy drying system for preheating sludge using exhaust gas of dryer. To apply a preheater in the drying system, the heat transfer characteristics between sewage sludge and the dryer outlet gas which has highly noncondensable gas should be evaluated. In the preheater, heat is exchanged between dryer outlet gas, which is a steam-air mixture and sewage sludge, so the heat transfer characteristics of condensation with noncondensable gas are crucial to determine the whole efficiency of the proposed drying system. It is well known that the performance of a heat exchanger is greatly reduced by the presence of noncondensable gas in a vapor stream [2]. Previous studies have analyzed the effect of noncondensable gas on steam or vapor condensation [3-6]. Zhu et al. [5] reported that steam condensation occurred outside a vertical tube, which is exactly the same as the preheater in the sewage sludge drying system. However, the inlet air mass fraction, the steam-air mixed gas inlet temperature, mixed gas velocity, and the geometry of the heat exchanger are different. Most of the obtained correlations are only applicable in the given system and the content of noncondensable gas is less than the proposed preheater, so the heat transfer characteristics of the proposed preheater should be investigated.

In this study, we investigated measuring the overall heat transfer coefficient for steam condensation in the presence of noncondensable gas, air, in the shell-and-tube type heat exchanger. We varied inlet steam flow rates which were related with noncondensable gas mass fractions, steam-air mixed gas inlet temperatures and sewage sludge (water for preliminary test) mass flow rates. The overall heat transfer coefficient was obtained according to experimental data, and used to scale up the proposed preheater in the sewage sludge drying system.

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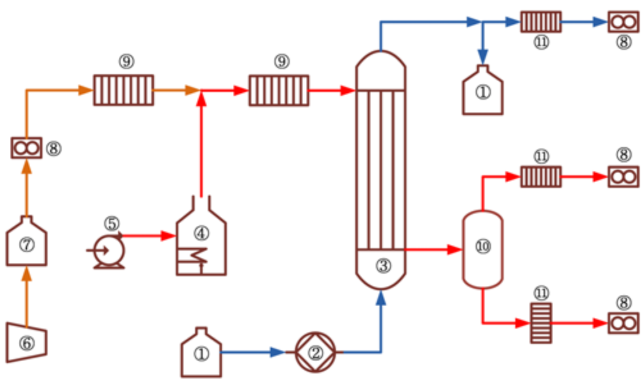

Fig. 1. Schematic of the experimental apparatus.

① Sludge storage tank	⑥ Air compressor
② Mono pump	⑦ Air storage tank
③ Shell-and-tube type heat exchanger	⑧ Flow meter
④ Steam generator	⑨ Gas preheater
⑤ Water pump	⑩ Flash vessel
	⑪ Condenser

EXPERIMENTS

1. Apparatus

Fig. 1 shows the schematic diagram of the experimental apparatus including a shell-and-tube type heat exchanger. The apparatus consists of a sludge storage tank, mono pump, steam generator, water pump, air compressor, air storage tank, flow meters, gas preheaters, flash vessel, and condensers. The sludge feed flow rate was controlled by rpm (revolutions per minute) of the inverter controlled mono pump, and the steam-air mixture flow rate was controlled by water pump and air flow meter. The temperature of the steam-air mixture stream was controlled by gas preheater. To set the same condition as a real drying system, air flow rate was fixed at 300 L/min. To measure the temperature of the shell-and-tube type heat exchanger, seven temperature indicators were installed to shell-side and tube-side, respectively, from bottom to top of the heat exchanger. After heat exchanging, flash vessel and condensers were installed to measure the amount of condensate and steam in the steam-air mixture and the amount of boil-up water vapor in the sludge stream was also measured by flow meter after condensing. The detailed design data of shell-and-tube type heat exchanger is summarized in Table 1.

2. Procedure

To investigate the performance of the proposed sludge preheater, we first used water as a tube-side material instead of sludge. In the preliminary experiment, the test variables were as follows: steam-air mixed gas inlet temperatures range from 95 to 120 °C; inlet air content, m_{air}/m_{steam} from 55 to 83%; tube-side water flow rate from 42 to 62 kg/h. For each case, the steady-state result was obtained during 10 min. After that, the sewage sludge was used as a tube-side material with varying tube-side sewage sludge flow rate from 42 to 62 kg/hr, steam-air mixed gas inlet temperature from 95 to 115 °C in the fixed inlet air content of 70% which is the same con-

Table 1. The detailed design data of shell-and-tube type heat exchanger

Items	Unit	Tube	Shell
Inside diameter	m	0.016	0.1652
Outside diameter	m	0.0217	-
Tube thickness	m	0.00285	-
No. of tubes	ea	10	-
Length	m	2	-
Tube pitch, p	m	-	0.0317
Baffle pitch, P	m	-	0.4
Baffle cut	%	-	25

Table 2. Experimental results using water as a tube-side material

No.	m_t (kg/h)	m_a (%)	Temperature (°C)				m_b (kg/h)	Heat transfer coefficient (W/m^{2}K)			
			T_{ha}	T_{hb}	T_{ca}	T_{cb}		U_o-exp	h_i	h_o	U_o-model
1	42.0	70	95.2	88.1	8.4	91.7	0	123.1	272.2	298.2	120.0
2	51.6	70	94.7	85.1	8.9	91.8	0	162.5	291.6	316.2	128.0
3	62.5	70	94.6	81.6	9.2	91.6	0	200.9	310.8	328.5	135.0
4	42.0	70	104.8	97.4	13.3	100.9	0.72	133.4	274.4	223.3	106.1
5	51.6	70	104.7	96.2	9.8	101.9	0.84	168.8	293.3	292.3	124.3
6	62.5	70	104.3	94.9	9.7	101.8	0.90	210.3	312.6	308.6	131.9
7	42.0	70	116.6	101.7	37.0	101.2	3.36	111.9	277.7	284.8	119.1
8	51.6	70	115.9	101.2	38.3	101.2	3.48	131.9	297.6	295.1	125.9
9	62.5	70	115.0	101.7	22.5	101.1	3.18	150.3	314.8	313.1	133.3
10	42.0	55	94.7	90.0	10.5	91.9	0	127.1	272.5	457.2	139.6
11	51.6	55	95.4	87.4	12.4	91.7	0	146.9	292.2	305.0	126.3
12	62.5	55	94.9	87.2	12.3	91.9	0	188.2	311.4	495.7	156.9
13	42.0	55	105.1	98.8	18.3	101.1	0.30	121.6	275.2	503.2	144.6
14	51.6	55	104.5	98.1	12.1	101.1	0.60	163.6	293.7	526.9	153.5
15	62.5	55	104.1	96.6	10.7	100.9	0.30	197.7	312.7	546.1	162.1
16	42.0	55	111.1	104.0	42.1	100.7	2.58	113.7	278.3	252.6	113.2
17	51.6	55	110.9	104.1	30.4	100.7	2.52	132.4	296.5	265.2	119.8
18	62.5	55	110.2	103.4	22.4	100.8	2.70	162.5	314.7	274.5	125.7
19	42.0	83	95.4	89.8	11.9	92.3	0	123.9	272.8	229.2	107.1
20	51.6	83	94.7	85.3	11.4	92.2	0	169.3	292.1	180.5	98.2
21	62.5	83	94.4	82.8	11.2	92.2	0	212.1	309.6	254.8	120.4
22	42.0	83	105.9	97.5	13.1	100.4	0.60	117.3	274.3	154.9	87.7
23	51.6	83	105.7	96.5	12.2	100.4	0.72	147.1	293.6	164.4	93.4
24	62.5	83	102.7	90.7	11.8	98.1	0.84	189.9	312.4	271.5	124.6
25	42.0	83	121.0	99.3	71.4	100.7	1.08	64.6	281.6	468.1	143.8
26	51.6	83	120.1	97.3	38.7	100.7	1.20	92.5	297.6	181.4	99.3
27	62.5	83	121.7	95.3	21.2	100.6	1.20	113.3	314.5	210.1	110.2

dition as the real drying system.

3. Heat Transfer Coefficient Calculation

In this study, tube-side material is water or sewage sludge which belongs to the viscous flow range. Tube-side heat transfer coefficient, h_i is calculated by following equation [7]:

$$\frac{h_i D}{k} = 2\left(\frac{\dot{m}c_p}{kL}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{1}$$

where D is inside diameter of the tube, k is thermal conductivity, $\dot{m}$ is mass flow rate, c_p is heat capacity, L is tube length, μ is viscosity, and μ_w is wall viscosity. The wall viscosity is calculated at the estimated wall temperature, T_w, which is obtained by the following equation [7]:

$$T_w = T + \Delta T_i \text{ for heating} \tag{2}$$

where T is the average fluid temperature and ΔT_i is calculated by following equation [7]:

$$\Delta T_i = \frac{1/h_i}{1/h_i + D_i/D_o h_o}\Delta T \tag{3}$$

where D_i is inside diameter of the tube, D_o is outside diameter of the tube, and ΔT is total temperature drop. Using Eqs. (2) and (3), the viscosity correction factor ϕ_v, $(\mu/\mu_w)^{0.14}$ is calculated. After obtaining the corrected heat transfer coefficient, ΔT_i and T_w is recalculated from Eqs. (2) and (3), and the viscosity correction has been terminated when the recalculated T_w is so close to the previous one. When water is used as a tube-side material, the liquid viscosity of water is expressed by the following equation [8]:

$$\mathrm{Ln}(\mu) = -24.71 + 4209/T + 0.04527T - 3.376E\text{-}05T^2 \tag{4}$$

where T in K and VISL in cP. When sewage sludge is used as a tube-side material, the viscosity correction factor is ignored in Eq. (1) since it is quite difficult to measure the viscosity of sewage sludge at each temperature condition in the experimental range. Also, the outlet temperature of sewage sludge maintains the similar condition within experimental ranges so that the effect of noncondensable gas on heat transfer coefficient can be analyzed with neglecting the viscosity correction factor.

The shell-side material is steam-air mixed gas, which contains noncondensable gas. The shell-side heat transfer coefficient, h_o, is calculated by following Zhu et al.'s correlation equation [5]:

$$h_o = 0.0342\left(\frac{k_{mg}}{L}\right)\left(\frac{m}{c_{pm}}\right)Re^{0.774} \tag{5}$$

where k_{mg} is thermal conductivity of mixed gas, L is tube length, c_{pm} is heat capacity of mixed gas, Re is Reynolds number of mixed gas, and m is defined by following equation:

$$m = \frac{dHE}{dT} \tag{6}$$

where HE is enthalpy of the humid air and T is bulk temperature of mixed gas.

RESULTS AND DISCUSSION

We summarized the experimental conditions and the individual heat transfer coefficient calculated by Eqs. (1) and (5) through the preliminary tests in Table 2. There were 27 experimental data obtained by varying tube-side flow rate, m_t, inlet air content, $m_a(m_{air}/m_{steam})$

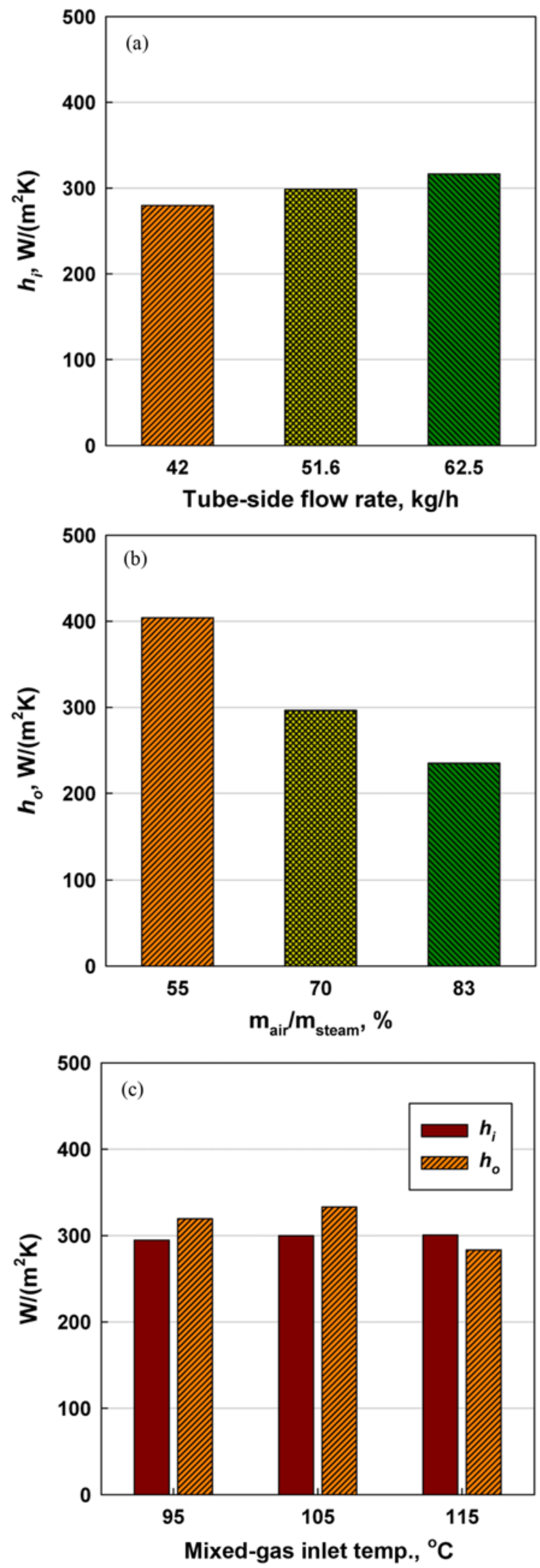

Fig. 2. Individual heat transfer coefficients in the preliminary tests.

Table 3. Experimental results using sewage sludge as a tube-side material

No.	m_t (kg/h)	m_a (%)	Temperature (°C)				m_b (kg/h)	Heat transfer coefficient (W/m^{2}K)			
			T_{ha}	T_{hb}	T_{ca}	T_{cb}		U_o-exp	h_i	h_o	U_o-model
1	42.0	70	95.0	90.3	20.2	91.5	0	96.5	280.9	230.2	109.0
2	51.6	70	94.3	89.2	20.6	90.6	0	116.4	300.6	240.3	115.3
3	62.5	70	95.7	89.4	20.8	91.1	0	132.8	320.1	233.0	117.2
4	42.0	70	104.0	100.5	21.7	99.6	0	90.9	283.0	156.3	89.3
5	51.6	70	104.7	100.2	21.8	99.8	0	108.7	302.8	167.5	95.7
6	62.5	70	104.5	98.8	21.0	99.5	0	132.4	322.2	190.4	105.7
7	42.0	70	113.7	106.5	21.5	100.7	0.18	64.3	283.7	85.7	60.8
8	51.6	70	110.9	105.8	22.5	100.4	0.24	85.0	303.7	109.9	73.7
9	62.5	70	112.7	106.7	22.5	99.3	0	89.2	323.4	129.5	83.9

and shell-side inlet temperature, T_{ha}. We measured boil-up flow rate, m_b in the tube-side in order to calculate the exact heat exchanged, which was calculated by following equation:

$$Q=m_tC_{p,w}(T_{cb}-T_{ca})+m_b\lambda \tag{7}$$

where $C_{p,w}$ is heat capacity of the water, T_{ca} is inlet temperature in the tube-side, T_{cb} is outlet temperature in the tube-side, and λ is heat of the vaporization.

In Table 2, the overall heat transfer coefficient, U_o-*exp* was calculated by the exchanged heat from Eq. (7), the heat transfer area based on the Table 1, and the logarithmic mean temperature difference (LMTD). Also, the overall heat transfer coefficient, U_o-*model* was obtained using individual tube-side heat transfer coefficient, h_i by Eq. (1) and the individual shell-side heat transfer coefficient, h_o by Eq. (5). Based on 27 experimental data, overall heat transfer coefficient, U_o-*exp* was somewhat greater than U_o-*model* obtained from model equations. The average overall heat transfer coefficient was around 149 W/m^{2}K by experiments, while that was around 124 W/m^{2}K by model in the whole experimental range.

Fig. 2 shows the individual heat transfer coefficients in relation to the tube-side flow rates, the inlet air contents, and the mixed-gas inlet temperatures. In Fig. 2(a), the tube-side heat transfer coefficient increased as the tube-side flow rate increased, as expected from Eq. (1). Fig. 2(b) shows that the shell-side heat transfer coefficient decreased as the inlet air content increased, since the performance of heat exchanger was reduced by increasing the amount of non-condensable gas in a vapor stream [2]. There was no effect of the mixed-gas inlet temperature on the each individual heat transfer coefficient in Fig. 2(c).

The sewage sludge was used as a tube-side material with varying tube-side sewage sludge mass flow rate from 42 to 62 kg/hr, steam-air mixed gas inlet temperature from 95 to 115 °C in the fixed inlet air content of 70%, which is the same condition as the real drying system. Table 3 shows nine experimental data obtained by varying tube-side flow rate, m_t, and shell-side inlet temperature, T_{ha}. The exact heat exchanged was calculated by Eq. (7) using a heat capacity of the sewage sludge instead of $C_{p,w}$. In this study, the heat capacity of the sewage sludge is assumed to be as follows:

$$C_{p,s}=mc\times C_{p,w}+(1-mc)\times C_{p,sand} \tag{8}$$

where $C_{p,s}$ is heat capacity of the sewage sludge, mc is the fraction of the moisture content in the sewage sludge (mc=0.8 as received), and $C_{p,sand}$ is heat capacity of the sand ($C_{p,sand}$=0.2 cal/gK [9]).

In Table 3, U_o-*exp*, h_i, h_o, and U_o-*model* were calculated by exactly the same way as the preliminary tests. Based on nine experimental data, the overall heat transfer coefficient, U_o-*exp* was similar to U_o-*model* obtained from model equations. The average overall heat transfer coefficient was around 102 W/m^{2}K by experiments, while that was around 95 W/m^{2}K by model in the whole experimental range. Compared with preliminary test results using water as a tube-side material, the overall heat transfer coefficient using water as a tube-side material has been somewhat greater than that using sewage sludge. That's because the average shell-side heat transfer coefficient of 295 W/m^{2}K using water as a tube-side material is greater than that of 171 W/m^{2}K using sewage sludge, from Tables 2 and 3 at the same inlet air content.

Fig. 3 shows the overall heat transfer coefficients obtained by both experimental data and heat transfer model for the preliminary tests and the sewage sludge tests. Evidently, some error exists between the experiments and the model since Zhu et al.'s correlation equa-

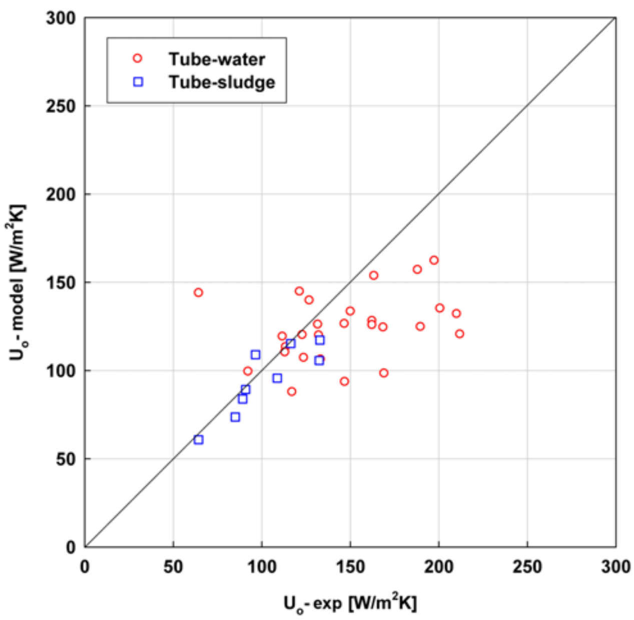

Fig. 3. The overall heat transfer coefficients obtained by both experimental data and heat transfer model for the preliminary tests and the sewage sludge tests.

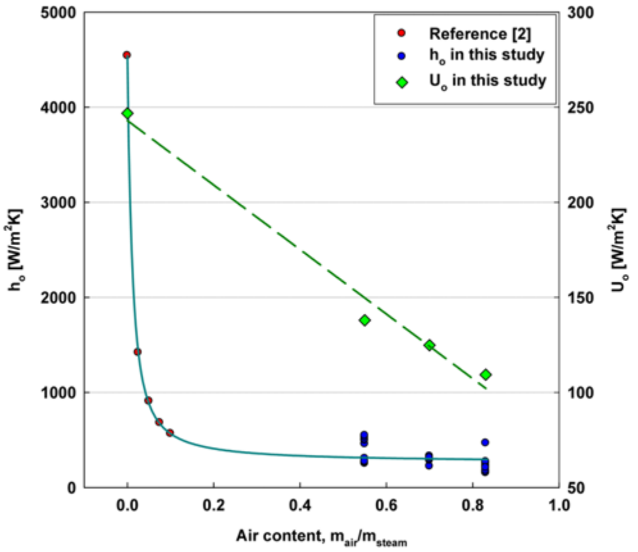

Fig. 4. The overall heat transfer coefficients and shell-side heat transfer coefficient in relation to the inlet air content in the steam-air mixed gas.

tion [5] for the shell-side heat transfer coefficient has been derived from the inlet air content of 30% to 80% and mixed-gas inlet temperature of 68 °C to 92 °C, which are somewhat different from the current experimental conditions. Fig. 4 shows the overall heat transfer coefficients and shell-side heat transfer coefficient in relation to the inlet air content in the steam-air mixed gas. It is evident that a significant decrease in the shell-side heat transfer coefficient results from the presence of small amounts of noncondensable gas. From the experiments, both the overall heat transfer coefficient and shell-side heat transfer coefficient decreased as the amount of noncondensable gas increased.

CONCLUSIONS

We studied the effect of noncondensable gas on steam condensation of the steam-air mixed gas in the shell-and-tube type preheater of the sewage drying system. In preliminary tests using water as a tube-side material, the average overall heat transfer coefficient was around 149 W/m^{2}K by experiments, while that was around 124 W/m^{2}K by model in the whole experimental range. When the sewage sludge was used, the average overall heat transfer coefficient was around 102 W/m^{2}K by experiments, while that was around 95 W/m^{2}K by model in the whole experimental range. The shell-side heat transfer coefficient calculated by a model showed that it decreased as the amount of noncondensable gas increased. From the experiments using sewage sludge as a tube-side material, the outlet temperature of sewage sludge was above 90 °C, which is high enough for reducing energy consumption in the dryer by preheating the sewage sludge.

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NOMENCLATURE

C_{pm} : heat capacity of mixed gas [cal/gK]
$C_{p,w}$: heat capacity of water [cal/gK]
$C_{p,s}$: heat capacity of sewage sludge [cal/gK]
$C_{p,sand}$: heat capacity of sand [cal/gK]
D_i : inside diameter of the tube [m]
D_o : outside diameter of the tube [m]
h_i : tube-side heat transfer coefficient [W/m^{2}K]
h_o : shell-side heat transfer coefficient [W/m^{2}K]
HE : enthalpy of the humid air [cal/g]
k : thermal conductivity [W/mK]
k_{mg} : thermal conductivity of mixed gas [W/mK]
L : tube length [m]
m_t : tube-side mass flow rate [kg/h]
m_a : inlet air content [%]
m_b : boil-up mass flow rate in the tube-side [kg/h]
m_c : fraction of the moisture content in the sewage sludge [0.8]
Re : Reynolds number
T : temperature [°C]
T_{ha} : shell-side inlet temperature [°C]
T_{hb} : shell-side outlet temperature [°C]
T_{ca} : tube-side inlet temperature [°C]
T_{cb} : tube-side outlet temperature [°C]
T_w : estimated wall temperature [°C]
U_o-exp : overall heat transfer coefficient using experimental data [W/m^{2}K]
U_o-model : overall heat transfer coefficient using model [W/m^{2}K]

Greek Symbols

λ : heat of vaporization for water [cal/g]
μ : viscosity [cP]
μ_w : wall viscosity [cP]
ϕ_v : viscosity correction factor

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