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UNIVERSAL METHOD OF CALCULATION OF RADIATION RECUPERATORS WITH MICROFINNED SURFACE

Notation

α_o – convection heat-transfer coefficient (smooth element), $W/(m^2 \cdot K)$,
α – convection heat-transfer coefficient (microfinned element), $W/(m^2 \cdot K)$,
α_g – heat-transfer coefficient of furnace gas, $W/(m^2 \cdot K)$,
ε_g – emissivity of furnace gas,
ε_w – emissivity of wall,
ε_f – micro-fin efficiency,
C_o – constant of radiation, $W/(m^2 \cdot K^4)$,
c_a – heat capacity of air, $kJ/(m^3 \cdot K)$,
c_g – heat capacity of furnace gas, $kJ/(m^3 \cdot K)$,
D, d – diameter, m,
F – heating surface area, m^2,
H – height of recuperator, m,
h – height of micro-fin, m,
k – over-all heat-transfer coefficient, $W/(m^2 \cdot K)$,
l – distance between micro-fins (scale), m,
λ_f – thermal conductivity, m,
r – radius, m,

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s – thickness, m,
Δp – pressure drop, Pa,
T_g, t_g – furnace gas temperature, K, °C,
T_w, t_w – wall temperature, K, °C,
T_a, t_a – air temperature, K, °C,
Δt_m – mean temperature difference, K,
Q – heat transfer rate, W, kW,
V – volumetric rate of fluid flow, m^3/s, m^3/h,
w – velocity, m/s,
ρ – density, kg/m^3,
η – dynamic viscosity coefficient, (kg·m)/s,
φ – ratio of microfinned surface,
λ – number of hydraulic resistance,
Re – Reynolds number,
Y – intensification function.

1. INTRODUCTION

Radiation recuperators are used for the recovery of heat from waste gases with industrial heat furnaces, glass furnaces, and foundry ones. This type of recuperator design is simple, tight and may be used for furnaces that have waste gas temperatures up to 1500°C. The radiation recuperators have problems with heat transfer in air side, saving of heat resistance materials, heat surface area, and value of over-all heat-transfer coefficient [1, 2, 7, 11, 13].

The over-all heat transfer coefficient in radiation recuperator is small, therefore intensification of forced convection in recuperator air channels is highly recommended. The intensification may be realized by heat transfer surface development methods, or direct action on air flow. The microfinned surface area methods [3, 4, 5] are in second group. The microfins made in air channel increased convective heat-transfer coefficient to air and over-all heat-transfer one in heat exchanger [12, 13, 14]. Heat transfer in radiation recuperators with microfinned surface is described by single-zone model [10] or zonal models [7, 8, 9]. The aim of this paper is universal calculation method of radiation recuperators allowing model investigations and geometric characteristics of micro-fin. Two mathematical models will be considered: single-zone or multi-zone model of recuperators with microfinned surface.

2. THE CALCULATIONS OF RADIATION RECUPERATORS WITH MICROFINNED SURFACE

In engineering calculations of radiation recuperators the heat balance or water equivalents method were used. To calculate the radiation of recuperator with microfinned surface single-zone or multi-zone models were elaborated [9, 10, 11]. By universal method, recuperators were calculated on air side, using ratio of microfinned surface. Heat transfer through recuperator wall is described by the following equation

$$Q = \frac{1}{\dfrac{F_m}{F_i \alpha_g} + \dfrac{F_m s}{F_i \lambda_f} + \dfrac{1}{\varepsilon_f \varepsilon_r \alpha}} \Delta t_m F_m \tag{1}$$

where φ is ratio of microfinned surface given by

$$\varphi = \frac{F_m}{F_i} \tag{2}$$

The symbols denote:

F_m – microfinned surface area,

F_i – inner surface area of center tube.

The over-all heat-transfer coefficient is described by equation

$$k = \frac{1}{\dfrac{\varphi}{\alpha_g} + \dfrac{\varphi \cdot s}{\lambda} + \dfrac{1}{\varepsilon_f \varepsilon_r \alpha}} \tag{3}$$

where:

α_g – heat-transfer coefficient of furnace gas,
α – heat-transfer coefficient to air,
s – thickness of center tube,
λ_f – thermal conductivity,
ε_r – correction factor.

The straight fin efficiency is:

$$\varepsilon_f = \frac{\mathrm{tg}h(mh)}{mh} \tag{4}$$

$$m = \sqrt{\frac{2\alpha}{\lambda_f \delta_f}} \tag{5}$$

where:

m – coefficient, 1/m,
h – height of fin,
δ_f – thickness of fin.

The straight fin efficiency is given in Table 1.

Table 1. Efficiency ε_f for a straight fin of constant thickness

$m{\cdot}h$	ε_f	$m{\cdot}h$	ε_f	$m{\cdot}h$	ε_f	$m{\cdot}h$	ε_f
0.1	0.997	0.8	0.830	1.5	0.603	2.2	0.444
0.2	0.987	0.9	0.796	1.6	0.576	2.3	0.426
0.3	0.971	1.0	0.762	1.7	0.550	2.4	0.410
0.4	0.950	1.1	0.728	1.8	0.526	2.5	0.395
0.5	0.924	1.2	0.695	1.9	0.503	2.6	0.380
0.6	0.895	1.3	0.667	2.0	0.482	2.7	0.367
0.7	0.863	1.4	0.632	2.1	0.462	2.8	0.355

Heat transfer to air from a circular fin can be approximated by a heat transfer from an equivalent surface of straight fin as follows

$$Q_1 = \varepsilon_r \, Q \tag{6}$$

The correction factor ε_r is substituted into equation (1). The factor is described by the following function

$$\varepsilon_r = f\left[\frac{1}{\cos h(m \cdot h)}, \frac{r_2}{r_1}\right] \tag{7}$$

where:
r_1 – inner radius of fin,
r_2 – outer radius of fin.

The function ε_r illustrates Figure 1.

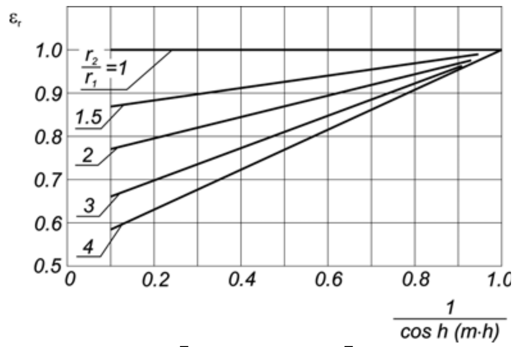

__Fig. 1.__ The correction factor $\varepsilon_r = f\left[\frac{1}{\cos h(m \cdot h)}, \frac{r_2}{r_1}\right]$ *for circular fins [1] of constant thickness*

The values of function $\frac{1}{\cos h(m \cdot h)}$ are given in Table 2 [1].

Table 2. Function $\frac{1}{\cos h(m \cdot h)}$

$(m \cdot h)$	$\frac{1}{\cos h(m \cdot h)}$	$(m \cdot h)$	$\frac{1}{\cos h(m \cdot h)}$	$(m \cdot h)$	$\frac{1}{\cos h(m \cdot h)}$
0.0	1	1.0	0.648	2.0	0.266
0.1	0.995	1.1	0.600	2.1	0.2415
0.2	0.980	1.2	0.552	2.2	0.219
0.3	0.956	1.3	0.508	2.3	0.1987
0.4	0.925	1.4	0.465	2.4	0.1805
0.5	0.887	1.5	0.425	2.5	0.1632
0.6	0.844	1.6	0.388	2.6	0.1478
0.7	0.797	1.7	0.354	2.7	0.1339
0.8	0.748	1.8	0.322	2.8	0.1212
0.9	0.698	1.9	0.293	–	–

The graph illustrated on Figure 1 shows the shape corrector factor ε_r for micro-fins is 1.0 $\left(\frac{r_2}{r_1} \to 1.0\right)$ invariant function $1/\cosh(m \cdot h)$. For radiation recuperators with microfinned surface universal calculation method were elaborated. This method includes equations (8)–(28) which describe heat-transfer and hydraulic resistance in recuperator with microfinned elements [4, 7, 8, 9, 10].

The outlet furnace gas temperature from recuperator can be calculated by equation

$$t''_g = t'_g \frac{c'_g}{c''_g} - \frac{V_a c_a \left(t''_a - t'_a\right)}{\xi V_g c''_g} \tag{8}$$

where:

- V_a – volumetric rate of air flow,
- c_a – heat capacity of air,
- V_g – volumetric rate of furnace gas flow,
- c'_g, c''_g – heat capacity of furnace gas,
- ξ – number of inner losses,
- t'_g – furnace gas temperature inlet to recuperator,
- t''_a – air preheat temperature outlet,
- t'_a – air temperature inlet.

The arithmetic mean temperature of furnace gas is

$$\bar{t}_g = \frac{t'_g + t''_g}{2} \tag{9}$$

The heat-transfer coefficient of furnace gas is given by

$$\alpha_g = \alpha_r + \alpha_c \tag{10}$$

where:

α_c – convection heat-transfer coefficient on furnace gas-side [11]

$$\alpha_c = \left(3.51 + 0.0031\bar{t}_g\right)\frac{w_g^{0,8}}{d_i^{0,2}} \tag{11}$$

$\bar{t}_g$ – arithmetic mean temperature of furnace gas,
w_g – velocity of furnace gas inside center tube,
d_i – inner diameter of center tube.

The radiation heat-transfer coefficient of furnace gas is [1, 11]

$$\alpha_r = 0.04\,\varepsilon_g\,\varepsilon'_w\left(\frac{T_m}{100}\right)^3 \tag{12}$$

where T_m – furnace gas and wall mean temperature.

The emissivity of furnace gas is described by equation [11]

$$\varepsilon_g = \beta_{CO_2}\,\varepsilon_{CO_2} + \beta_{H_2O}\,\varepsilon_{H_2O} - \Delta\varepsilon_g \tag{13}$$

where:

ε_{CO_2} – emissivity of carbon dioxide,
ε_{H_2O} – emissivity of water wapour,
β_{CO_2}, β_{H_2O}, $\Delta\varepsilon_g$ – correction factors.

The effective emissivity of wall is expressed by [7]

$$\varepsilon'_w = \frac{\varepsilon_w + 1}{2} \tag{14}$$

The convective heat-transfer coefficient to air (microfinned element) is [7, 9]

$$\alpha = (1+Y)(3.57+0.00174\,\bar{t}_a)\frac{w_a^{0.8}}{(D-d_r)^{0.2}} \tag{15}$$

where:

Y – intensification function

$$Y = \frac{\alpha-\alpha_o}{\alpha} = 36.52\left(\frac{l}{h}\right)^{0.35} e^{-0.037\frac{l}{h}}\,\mathrm{Re}^{-0.36} \tag{16}$$

$$4000 \le \mathrm{Re} < 12\,000\,,\ 5 \le \frac{l}{h} \le 40\,,\ h > h_r > 0,$$

w_a – velocity of air,
D – diameter of inner cover,
d_r – outer diameter of center tube,
l – micro-fin pitch,
h – height of micro-fin,
h_r – height of roughness.

The symbol t_a denotes air arithmetic mean temperature

$$\bar{t}_a = \frac{t_a' + t_a''}{2} \tag{17}$$

The ratio of microfinned surface is

$$\varphi = \frac{F_l}{F_i} \tag{18}$$

with surface areas given by:

– micro-fins

$$F_l = \pi d_r l - \pi d_r \delta_f + 2\left[(d_r+h)^2 - d_r^2\right]\frac{\pi}{4}, \qquad \mathrm{m^2/pitch} \tag{19}$$

– inner surface of the tube

$$F_i = \pi d_i l, \qquad \mathrm{m^2/pitch} \tag{20}$$

where:

d_i – inner diameter of center tube,
d_r – outer diameter of center tube,
δ_f – thickness of micro-fin,
l – micro-fins pitch.

The microfinned surface area is

$$F_m = F_l \frac{1.0}{l} \text{ m}^2/\text{m} \tag{21}$$

The over-all heat-transfer coefficient is described by equation

$$k = \frac{1}{\frac{\varphi}{\alpha_g} + \frac{\varphi \cdot s}{\lambda_f} + \frac{1}{\varepsilon_f\, \alpha}} \tag{22}$$

The wall temperature can be calculated by

$$t_w = t_a + \frac{k}{\alpha}\left(\bar{t}_g - \bar{t}_a\right) \tag{23}$$

The logarithmic mean temperature difference is

$$\Delta t_m = \frac{\Delta t' - \Delta t''}{\ln \frac{\Delta t'}{\Delta t''}} \tag{24}$$

The heat transfer rate is

$$Q = V_a\, c_a\, \Delta t_a \tag{25}$$

The height of recuperator is

$$H = \frac{Q}{k\, \Delta t_m F_m} \tag{26}$$

The pressure drop of air is [7, 9]:

$$\Delta p_a = \lambda \frac{w_a^2 \rho_a}{2} \frac{H}{D - d_r} \tag{27}$$

$$\lambda = 0.316 \left(\frac{r}{h}\right)^{-0.76} \left(\frac{l}{h}\right)^{0.56} e^{-0.061\frac{l}{h}} \tag{28}$$

$$2.67 \le \frac{r}{h} \le 16, \quad 5 \le \frac{l}{h} \le 40, \quad h > h_r > 0$$

where r – equivalent radius.

3. THE CALCULATIONS OF RADIATION RECUPERATOR WITH MICROFINNED SURFACE TO HEAT FURNACE

Radiation recuperator is installed in heat furnace flue channel. This is parallel flow recuperator. Furnace gas flows by centre tube about 1.0 m diameter. Across microfinned center tube is placed coaxially in inner cover, about 1.05 diameter. Preheat air flows by gap between center tube and inner cover.

The recuperator determine the following conditions:

- volumetric rate of furnace gas flow V_g = 1130 m^3/h (0.314 m^3/s),
- furnace gas temperature inlet to recuperator t'_g = 1250°C,
- concentration of carbon dioxide in furnace gas [CO_2] = 10%,
- concentration of water vapour in furnace gas [H_2O] = 18%,
- volumetric rate of air flow V_a = 1030 m^3/h (0.286 m^3/s),
- air preheat temperature t''_a = 500°C,
- inner diameter of center tube d_i = 1.0 m,
- thickness of center tube wall s = 0.005 m,
- outer diameter of center tube d_r = 1.01 m,
- diameter of inner cover D = 1.05 m.

The furnace gas temperature outlet from recuperator is:

$$t''_g = t'_g \frac{c'_g}{c''_g} - \frac{V_a c_a \left(t''_a - t'_a\right)}{\xi V_g c''_g} = 1250 \cdot 1.06 - \frac{0.286 \cdot 1.33 \cdot 500}{0.9 \cdot 0.314 \cdot 1.55} = 891^{\mathrm{o}}\mathrm{C},$$

where:

t'_g = 1250°C – furnace gas temperature inlet to recuperator,
c'_g = 1.64 kJ/(m^3·K), c''_g = 1.55 kJ/(m^3·K) – heat capacity of furnace gas,
ξ = 0.9 – number of inner losses,
t'_a = 0°C – air temperature inlet,
t''_a = 500°C – air preheat temperature outlet,
c_a = 1.33 kJ/(m^3·K) – heat capacity of air.

The furnace gas mean temperature is:

$$\bar{t}_g = \frac{1250 + 891}{2} = 1071^{\mathrm{o}}\mathrm{C},$$

$$\bar{T}_g = 1344 \text{ K}.$$

The emissivity of furnace gas [11] equals:

$$\varepsilon_g = \beta_{CO_2}\,\varepsilon_{CO_2} + \beta_{H_2O}\,\varepsilon_{H_2O} - \Delta\varepsilon_g = 0.10 + 1.1 \cdot 0.11 = 0.22,$$

layer thickness $s = 0.9\, d_i = 0.9 \cdot 1.0 = 0.9$ m,

emissivity of carbon dioxide $(p \cdot s)_{CO_2} = 0.10 \cdot 0.9 \cdot 98.1 = 8.8$ kPa , $\varepsilon_{CO_2} = 0.10$,

emissivity of water vapour $(p \cdot s)_{H_2O} = 0.18 \cdot 0.9 \cdot 98.1 = 15.9$ kPa , $\varepsilon_{H_2O} = 0.11$,

correction factors: $\beta_{CO_2} = 1.0, \quad \beta_{H_2O} = 1.1, \quad \Delta\varepsilon_g = 1.0.$

The effective emissivity of center tube [7] is

$$\varepsilon'_w = \frac{\varepsilon_w + 1}{2} = \frac{0.8 + 1}{2} = 0.9.$$

The mean temperature is

$$T_m = \frac{T_g + T_w}{2} = \frac{1344 + 864}{2} = 1104 \text{ K}.$$

The radiation heat-transfer coefficient equals

$$\alpha_r = 0.04\,\varepsilon_g\,\varepsilon'_w\,C_o\left(\frac{T_m}{100}\right)^3 = 0.04 \cdot 0.22 \cdot 0.9 \cdot 5.67\left(\frac{1104}{100}\right)^3 = 60.4 \text{ W/(m}^2 \cdot \text{K)}.$$

The velocity of furnace gas is

$$w_g = \frac{V_g}{\frac{\pi d_i^2}{4}} = \frac{0.314}{\frac{\pi \cdot 1.0^2}{4}} = 0.4 \text{ m/s}.$$

The convection heat-transfer coefficient of furnace gas is

$$\alpha_c = \left(3.51 + 0.00311\,\bar{t}_g\right)\frac{w_g^{0.8}}{d_i^{0.2}} = (3.51 + 0.00311 \cdot 1071)\frac{0.4^{0.8}}{1.0^{0.2}} = 3.3 \text{W/(m}^2 \cdot \text{K)}.$$

The heat-transfer coefficient of furnace gas equals

$$\alpha_g = \alpha_r + \alpha_c = 60.4 + 3.3 = 63.7 \text{ W/(m}^2 \cdot \text{K)}.$$

The air mean temperature is

$$\bar{t}_a = \frac{t''_a + t'_a}{2} = \frac{500+0}{2} = 250°\text{C},$$

$$\bar{T}_a = 523 \text{ K}.$$

The velocity of air is

$$w_a = \frac{V_a}{\frac{\pi}{4}\left(D^2 - d_r^2\right)} = \frac{0.286}{\frac{\pi}{4}\left(1.05^2 - 1.01\right)} = 4.4 \text{ m/s}.$$

The equivalent diameter of air gap is

$$d_h = D - d_r = 1.05 - 1.01 = 0.04 \text{ m}.$$

The convection heat-transfer coefficient (smooth center tube) to air equals

$$\alpha_o = \left(3.57 + 0.00174\,\bar{t}_a\right)\frac{w_a^{0.8}}{d_h^{0.2}} = \left(3.57 + 0.00174 \cdot 250\right)\frac{4.4^{0.8}}{0.04^{0.2}} = 24.7 \text{ W/(m}^2 \cdot \text{K)}.$$

The Reynolds number in air gap is

$$\text{Re} = \frac{w_a \cdot d_h\, \rho_o}{\eta} = \frac{4.4 \cdot 0.04 \cdot 1.27}{27.04 \cdot 10^{-6}} = 8266$$

where:

w_a = 4.4 m/s – velocity of air,

ρ_o = 1.27 kg/m^3 – density of air,

p_o = 1000 hPa,

T_o = 273 K,

d_h = 0.04 m – hydraulic diameter,

η = 27.04 · 10^{-6} (kg · m)/s – dynamic viscosity factor.

The intensification function is

$$Y = 36.52\left(\frac{l}{h}\right)^{0.35} e^{-0.037\frac{l}{h}}\, \text{Re}^{-0.36} = 36.52 \cdot 10^{0.35}\, e^{-0.037 \cdot 10}\, 8266^{-0.36} = 2.19.$$

The heat-transfer coefficient of microfinned center tube is

$\alpha = (1 + Y)\, \alpha_o = (1 + 2.19) \cdot 24.7 = 78.8$ W/(m$^2 \cdot$ K).

The coefficient m is

$$m = \sqrt{\frac{2\alpha}{\lambda_f\, \delta_f}} = \sqrt{\frac{2 \cdot 78.8}{25 \cdot 0.001}} = 79.4 \text{ l/m},$$

where:

$\alpha = 78.8$ W/(m$^2 \cdot$ K) – convective heat-transfer coefficient to air,
$\lambda_f = 25$ W/(m $\cdot$ K) – thermal conductivity,
$\delta_f = 0.001$ m – thickness of micro-fin,
$h = 0.04$ m – height of micro-fin,
$m \cdot h$ = $78.8 \cdot 0.004 = 0.32$,
$\varepsilon_f = 0.967$ – micro-fin efficiency.

The microfinned surface area (notation by Fig. 2) is:

$$F_1 = \pi d_r\, l - \pi d_r\, \delta_f - 2[(d_r + h)^2 - d_r^2] \cdot \frac{\pi}{4} = \pi \cdot 1.01 \cdot 0.04 - \pi \cdot 1.01 \cdot 0.001 +$$

$$+ 2[(1.01 + 0.004)^2 - 1.01^2] \cdot \frac{\pi}{4} = 0.137 \text{ m}^2\text{/pitch},$$

$$F_m = F_1 \cdot \frac{1.0}{l} = 0.137 \cdot \frac{1.0}{0.04} = 3.425 \text{ m}^2\text{/m},$$

where:

$d_r = 1.01$ m – outer diameter of center tube,
$h = 0.004$ m – height of micro-fin,
$l = 0.04$ m – micro-fin pitch,
$\delta_f = 0.001$ m – thickness of micro-fin.

The inner surface area of center tube is

$F_i = \pi d_i\, l = \pi \cdot 1.0 \cdot 0.04 = 0.126$ m^2/pitch,

where:

$d_i = 1.0$ m – inner diameter of center tube,
$l = 0.04$ m – micro-fin pitch.

The ratio of microfinned surface equals

$$\varphi = \frac{F_l}{F_i} = \frac{0.137}{0.127} = 1.09.$$

The over-all heat transfer coefficient is

$$k = \frac{1}{\dfrac{\varphi}{\alpha_g} + \dfrac{\varphi \cdot s}{\lambda_f} + \dfrac{1}{\varepsilon_f\, \alpha}} = \frac{1}{\dfrac{1.09}{63.7} + \dfrac{1.09 \cdot 0.005}{25} + \dfrac{1}{0.967 \cdot 78.8}} = 32.8\ \text{W/(m}^2 \cdot \text{K).}$$

The wall temperature is

$$t_w = t_a + \frac{k}{\alpha}\left(\bar{t}_g - \bar{t}_a\right) = 250 + \frac{32.8}{78.8}\,(1071 - 250) = 591°\text{C}\ ,\ \ T_w = 864\ \text{K}.$$

The logarithmic mean temperature difference equals

$$\Delta t_m = \frac{\Delta t' - \Delta t''}{\ln \dfrac{\Delta t'}{\Delta t''}} = \frac{1250 - (891 - 500)}{\ln \dfrac{1250}{391}} = 739\ \text{K}.$$

The heat-transfer rate is

$$Q_a = V_a\, c_a\, \Delta t_a = 0.286 \cdot 1330 \cdot 500 = 190\ 190\ \text{W}.$$

The height of recuperator is

$$H = \frac{Q_a}{k\, \Delta t_m\, F_m} = \frac{190190}{32.8 \cdot 739 \cdot 3.425} = 2.29\ \text{m}.$$

The number of hydraulic resistance in air channel is

$$\lambda = 0.316\, \left(\frac{r}{h}\right)^{-0.76} \cdot \left(\frac{l}{h}\right)^{-0.56} e^{-0.061\frac{l}{h}} = 0.316\left(\frac{0.02}{0.004}\right)^{-0.76} \cdot 10^{-0.56} \cdot e^{-0.061 \cdot 10} = 0.18,$$

where:

$r = 0.02$ m – equivalent hydraulic radius,
$h = 0.004$ m – height of micro-fin,
$l = 0.04$ m – micro-fin pitch.

The pressure drop of air equals

$$\Delta p_a = \lambda \frac{w_a^2 \rho_o}{2} \cdot \frac{H}{D - d_r} = 0.18 \frac{4.4^2 \cdot 1.27}{2} \cdot \frac{2.29}{1.05 - 1.01} = 127 \text{ Pa},$$

where:

w_a = 4.4 m/s – velocity of air,
ρ_o = 1.27 kg/m^3 – density of air,
p_o = 1000 hPa,
T_o = 273 K,
H = 2.28 m – height of recuperator,
$D - d_r$ = 0.04 m – equivalent hydraulic diameter.

To make heat calculation by multi-zone model [9] the recuperator was divided into five zones receiving preheated air with temperatures:

limite zone 1 – 100°C,
limite zone 2 – 200°C,
limite zone 3 – 300°C,
limite zone 4 – 400°C,
limite zone 5 – 500°C.

The values of calculations are given in Table 3.

Table 3. Parameters of zones calculates by multi-zone model

Parameters	Unit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Air temperature outlet	°C	100	200	300	400	500
Furnace gas temperature outlet	°C	1178	1118	1042	935	861
Mean temperature of furnace gas	°C	1214	1118	1080	989	898
Mean temperature of air	°C	50	150	250	350	450
Radiation heat-transfer coefficient of furnace gas	W/(m^2·K)	65.9	62.8	60.3	53.6	49.2
Convection heat-transfer coefficient of furnace gas	W/(m^2·K)	3.5	3.4	3.3	3.2	3.1
Heat-transfer coefficient of furnace gas	W/(m^2·K)	69.4	66.2	63.6	56.8	52.3
Intensification function	–	1.94	2.08	2.19	2.30	2.40
Heat-transfer coefficient to air	W/(m^2·K)	66.4	72.7	78.8	85.1	91.5
Over all heat-transfer coefficient	W/(m^2·K)	31.7	32.5	32.9	31.9	30.9
Wall temperature	°C	606	596	597	588	601
Mean temperature difference	K	1162	1000	886	686	443
Heat transfer rate	kW	36.6	36.9	37.2	37.4	38.0
Microfinned surface area	m^2/m	3.425	3.425	3.425	3.425	3.425
Height of zone	m	0.29	0.33	0.40	0.50	0.81

The height of recuperator is

$$H' = H_1 + H_2 + H_3 + H_4 + H_5 = 0.29 + 0.33 + 0.40 + 0.50 + 0.81 = 2.33 \text{ m}.$$

Relative difference height of recuperator calculates by single-zone or multi-zone model is

$$\frac{\Delta H}{H} \cdot 100\% = \frac{2.33 - 2.29}{2.33} \cdot 100\% = 1,7\%.$$

The radiation recuperator with microfinned surface illustrates Figure 2.

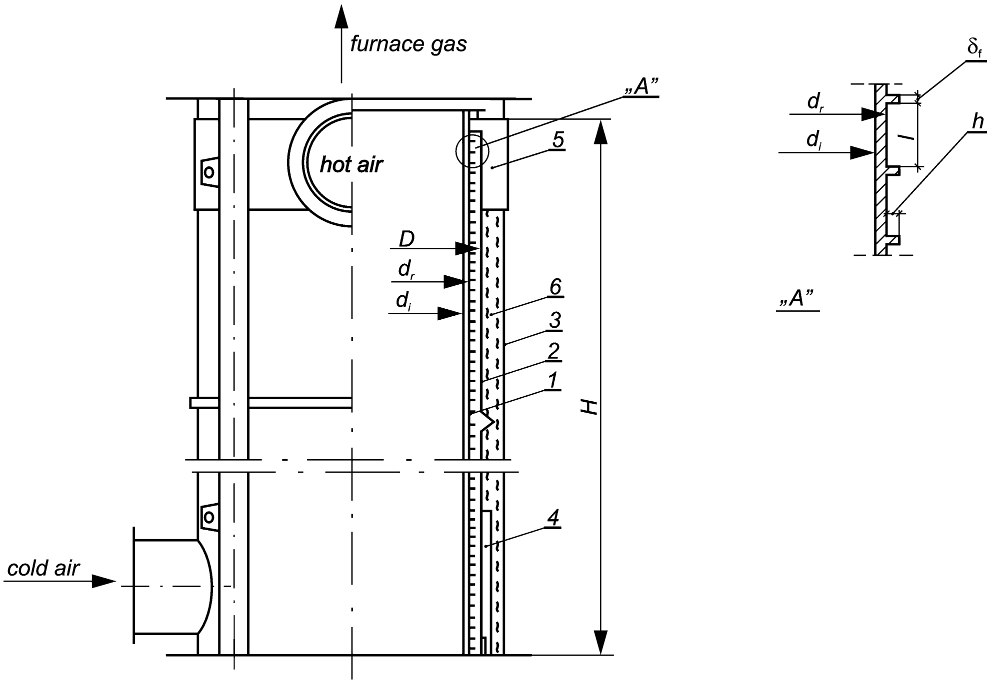

Fig. 2. *Radiation recuperator: 1 – center tube with micro-fines, 2 – inner cover, 3 – outer cover, 4 – inlet chamber, 5 – outlet chamber, 6 – heat insulation*

4. INFERENCES

– The radiation recuperators with microfinned surface can be used for the recovery of heat from waste gas with foundry furnaces, glass-furnaces and heat ovens. The furnace that is equipped with radiation recuperator must be automatically reguled and controlled.

– Universal calculation method includes geometric recuperator parameters: ratio of microfinned surface, microfinned surface area, and operation characteristics: heat-transfer ratio, over-all heat-transfer coefficient, temperature difference between furnace gas and air and pressure drop of air.
– The calculation method for convective heat transfer coefficient and hydraulic resistance number of microfinned elements is valid for the following ranges: $4000 \leq \mathrm{Re} \leq 12\,000$, $5 \leq \frac{l}{h} \leq 40$, $2{,}67 \leq \frac{r}{h} \leq 16$, $h > h_r > 0$.
– In this range of numbers the intensification function is: $0 \leq Y \leq 2.9$, and the number of hydraulic resistance is: $0.026 \leq \lambda \leq 0.27$.
– If micro-fin pitch approaches to zero, height of micro-fin is equivalent to the surface roughness, function $Y = 0$.
– If the efficiency microfin is greater than 0.90, then correction shape factor is 1.0.
– Universal method of calculation developed in the paper makes possible the recuperator's design to industrial furnaces. Relative difference in the height of recuperator calculated by single-zone and multi-zone model does not exceed 1.7%.

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