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MATHEMATICAL MODEL FOR NEW TYPE OF HEAT ECONOMIZER

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Abstract. Many industrial boilers (for example CR 9) use cold water and evacuate roast gases at temperatures upper 160°C, whose warmth is dissipated in atmosphere. In this article, we present a new type of heat exchanger (named heat economizer) built in concrete, allowing to heat cold water of boilers just with useful recuperative heat of roast gases. The heat economizer is composed of more prefab elements (panels). First we will describe these elements, the mathematical gas-hydrodynamic model and afterwards theirs connections and the building of heat economizer. The use of the heat economizer increases the efficiency of boilers with until 7% and it also reduces the thermal pollution in the area.

1. PRESENTATION OF PREFAB ELEMENTS

The heat economizer is made of plane panels, prefabricated from compact concrete, with mark 600 (resistant to corrosion-proof), [1]. For objectification, suppose each element will warm water from 15° to 65°C, designed to industrial consumption (or urban), with the heat of evacuated roast gases from CET, at a temperature of 180°C, [2]. Gases will be cooled up to 80°C (figure 1), [3], the temperature which still assures thermogravitational progress with a view to dispersing harmful components of roast gases on the largest surface; for diminishing negative effects thanks to cooling gases, dynamic compression of gases will increase by its exit through single stove-pipe. These facts will increase the height of dispersion stove-pipe, surpassing the existent in neighboring stove-pipes.

The mean difference between temperatures of thermal agents is:

$$\Delta T_m = (115 - 65)/\ln(115/65) \simeq 88 \text{ K}.$$

Globally, the pollution will be more reduced, by useful cooling of roast gases from 180°C to 80°C and implicitly, avoid the consumption of fuel necessary to warm

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water; the energetic efficiency of the boilers will increase with 4 up to 7%, [2].

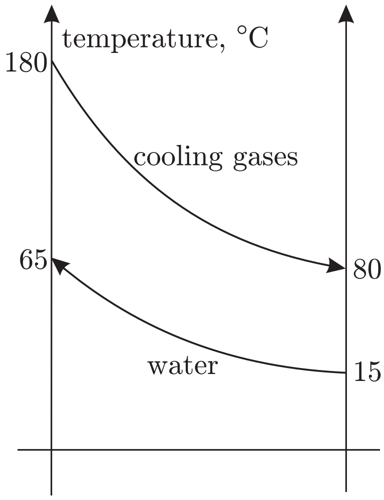


Figure 1. The mean difference between temperatures of thermal agents

The cooling up to 80°C will be made in all periods where the atmospheric air is hot enough and dried for resulted gases to form one relatively transparent jet; more seldom in the cold period, when the jet can become unclear owing to condensation of the humidity of gases or when almost all used fuel contain sulphur; then one part of the exhausted gaseous flux absorbed by the installation of the heat saver will by-pass the surfaces for heat exchanges (panels) through the by-pass channels, in this way the rising temperature of hung-up gases in atmosphere and decreasing until annihilation the "acid rain" (which can endanger the exterior of neighboring buildings even for a short term).

The prefab elements of the heat economizer are identical plane panels of compact concrete, with high mark, with rectangular form, with thickness of 50 mm, in which one parallel pipes ensemble of 13.5 × 2.25 mm is involved through which water moves in stages by cross flow, joined in backwash in bearing by movement of gases through free spaces between neighboring panels, spaces with breadth of 15 mm. The concrete is of the kind used at tubes by precompressed concrete Premo, for water pipes under pressure, buried into the ground, in harder conditions than contemplated prefabs. The concrete is prepared in compact aggregates, with necessary granulometry for a maximum compactness, using both disperse reinforcement (from wire of 0.5 mm, cut at length of 5-10 mm) and regulate oriented reinforcement, which contributes to increase thermal conductivity at minimum 3.0 W / m.K. The migration of humidity through the concrete towards relatively cold tubes of the involved register is negligible, and water which nevertheless would penetrate cancels chemical aggression in contact with concrete armour, [4].

For the reinforcement of the concrete panel and for increasing the main thermal conductivity of the concrete on perpendicular direction on the pipes 13.5 × 2.25 mm, platbands of 20 × 2 mm are previewed, equidistant with 30 mm. The rise of conductivity determined by

$$\Delta k = 20 \times 2 \times (54.4 - 1.5)/(50 \times 30) \simeq 1.41\mathrm{W/m} \cdot \mathrm{K}.$$

The compact concrete of plates with density of about 2.300 $\mathrm{Kg/m^3}$ has a mean thermic conductivity of $\lambda = 1.55$ W/m·K and contribution of metallic "forcemeat" (about 100 $\mathrm{kg/m^3}$ disperse reinforcement) is of 0.4 W/m·K. Therefore, in the width of steel platbands we will consider $\lambda = 3.36$ W/m·K. The distance between the tubes axes is of 100 mm, and the distance of conductive transport of heat lengthwise of platbands varies between 86.5 and 100 mm, [1].

2. MATHEMATICAL GAS-HYDRODYNAMIC MODEL

We introduce the notations:

- s = the area of unit section from broad of panel (0.05 $\mathrm{m^2/m}$, the thickness of the panel being of 50 mm);
- d = the distance between the tubes axes (100 mm);
- λ = the mean thermic conductivity of the panel (3.36 W/m·K);
- t = the temperature in the panel (considered, for understanding, as depending only on distance x from the axis at the nearst tube);
- t_g = the temperature of gases;
- t_0 = the temperature of tube walls (compared with a flat wall, normal on plate, with $x = 0$);
- α = the convective thermic transmissivity (superficial exchange coefficient through convection of gases at the faces of the panel).

For this heat economizer, we have the differential thermic equation

$$\frac{\mathrm{d}}{\mathrm{d}\,x}\left(-\lambda s \frac{\mathrm{d}\,t}{\mathrm{d}\,x}\right) = 2\alpha(t_g - t).$$

That is

$$\frac{\mathrm{d}^2 t}{\mathrm{d}\,x^2} - r^2 t = -r^2 t_g, \tag{2.1}$$

where $r = (2\alpha/\lambda \cdot s)^{1/2}$. Through integration, it follows

$$t = t_g + Ae^{rx} + Be^{-rx}$$

with A, B constants which are determined from the boundary value conditions with $t = t_0$, for $x = 0$ and extreme t ($\mathrm{d}\,t/\mathrm{d}\,x = 0$) for $x = d/2$. It follows $t_0 - t_g = A + B$ and $Ae^{rd/2} - Be^{-rd/2} = 0$, from where:

$$A = \frac{t_0 - t_g}{1 + e^{rd}} \quad \text{and} \quad B = \frac{t_0 - t_g}{1 + e^{rd}} e^{rd}$$

and finally

$$t = t_g - \frac{t_0 - t_g}{1 + e^{rd}} [e^{rd} + e^{r(d-x)}].$$

The heat flux received by a tube with one meter length is:

$$q_0 = -2\lambda s \frac{\mathrm{d}\, t}{\mathrm{d}\, x}\bigg|_{x=0} \quad \text{or} \quad q_0 = -2\lambda s r \Delta t_e \frac{e^{rd}-1}{e^{rd}+1}, \tag{2.2}$$

where Δt_e is the difference between the gases temperatures and that of the exterior face of the tube (t_0).

The gases flow vertically, from top to bottom, to facilitate the evacuation of acid humidity condensed on panels; they move through the spaces between panels, vertically mounted, spaced with 15 mm each. On the basis of some orientation antecalculations, the speed of 8 mm/s is elected. With the purpose of reducing the errors due to some mean temperatures, which cannot be the same on great intervals both for the thermokinetic and for their flow dynamics, calculations are performed on two zones, one were gases get cool from 180° to 130°C and another from 130°C to 80°C. A usual composition of roast gases in volumetric percents is the following: 73% N_2; 13.5% CO_2; 9.5% H_2O; 3.5% O_2; 0.5% SO_2. At mean temperatures of 155°C and respectively 105°C of both zones, the gases have each the density:

$$\rho_{155} = \frac{p}{RT}\sum r_i\mu_i = [1/8314\cdot(273+155)]\cdot(0.730\cdot 28 + 0.135\cdot 44 + 0.095\cdot 18 \\ +0.035\cdot 32 + 0.005\cdot 64)\cdot 10^5 \simeq 0.83\ \text{kg/m}^3$$

and respectively $\rho_{105} = 0.94$ kg/m^3.

The dynamic sliminesses are:

$$\eta_{155} = \frac{1}{\sum \frac{r_i}{\mu_i}} = 10^{-6}\left(\frac{0.730}{22.7}+\frac{0.135}{20.2}+\frac{0.095}{14.5}+\frac{0.035}{26.7}+\frac{0.005}{18.3}\right)^{-1} \simeq 21.2\cdot 10^{-6}\ \text{Pa}\cdot\text{s}$$

and respectively $\eta_{105} = 18.9\cdot 10^{-6}$ Pa·s.

It follows the cinematic sliminesses:

$$\nu_{155} = 21.2\cdot 10^{-6}/0.83 \simeq 25.4\cdot 10^{-6}\ \text{m}^2/\text{s} \quad \text{and respectively} \quad \nu_{105} = 20.1\cdot 10^{-6} m^2/s.$$

The Reynolds criteria are:

$$\text{Re}_{155} = 8\cdot\left(1+\frac{155}{273}\right)\cdot\frac{2\cdot 24\cdot 10^{-3}}{24.4\cdot 10^{-6}} = 23{,}702, \quad \text{respectively} \quad \text{Re}_{105} = 26{,}585,$$

which place the gas in the turbulent flow zone. Nusselt criteria will have the values:

$$\text{Nu}_{155} = 0.023\cdot 23.702^{0.8}\cdot 0.68^{0.3} \simeq 64.76 \quad \text{and respectively} \quad \text{Nu}_{105} = 70.98.$$

By technical publications [1], [2], [3], thermic conductivities of burning gases (in usual composition) are 0.035 and respectively 0.0309 W/m·K. They are used in the computation of the convective total exchange superficial coefficients:

$$k_{155} = 64.76\cdot\frac{0.0305}{2\cdot 0.024} \simeq 47.90 \quad \text{and respectively} \quad k_{105} = 45.70\,\text{W/m}^2\cdot\text{K}.$$

Volumetric caloric specific capacities (or specific heat), at constant pressure of gases 180○C, 130°C and 80°C are, respectively:

$$\begin{aligned} c_V^{180} &= 0.730 \cdot 0.311 + 0.135 \cdot 0.422 + 0.095 \cdot 0.363 + 0.035 \cdot 0.138 + 0.005 \cdot 0.44 \\ &\simeq 0.333\,\mathrm{Kcal/m_n^3} \cdot \mathrm{K} = 1.396\mathrm{KJ/m_n^3} \cdot \mathrm{K} \end{aligned}$$

and respectively 1.390 and 1.384 KJ/m^{3}n·K.

Taking into account the position of the heat economizer and the reducing number of the prefab elements and junctions, prefab panels of 2 m broad are chosen. On a panel, the gases cede in the warmer zone:

$$Q_g = 8 \cdot 0.024 \cdot 2 \cdot (1.396 \cdot 180 - 1.390 \cdot 130) \simeq 27.10\,\mathrm{kW} \tag{2.3}$$

and in the other zone 26.87 kW. Totally, one panel takes over from the gases 53.97 kW. The temperature of water increases from 15° to 40°C in the less hot zone and from 40° to 65°C in the warmer zone. The mean differences between the temperatures of thermal agents are:

$$\Delta t_1 = \frac{(180-130)-(130-40)}{\ln \dfrac{180-130}{130-40}} \simeq 102.0\,\mathrm{K} \quad \text{and respectively,} \quad \Delta t_2 \simeq 76,8\,\mathrm{K}.$$

The water flux which flows through the panel is

$$D_w = \frac{53.974}{4.193 \cdot 65 - 4.192 \cdot 15} \simeq 0.257\,\mathrm{kg/s} = 0.263\,\mathrm{l/s} = 0.944\,\mathrm{m^3/h}. \tag{2.4}$$

On one hand, water must flow with Re criterion as large as possible, so that the absorption of heat from the interior face of the tube should require small temperature drops and on the other hand, Reynolds criterion must be as small as possible so that the difference of pressure linked to water recirculation should be techno-economical acceptable. It is sufficient to respect the condition Re > 7000 at the water entrance in panel (with 15°C, minimal temperature and maximal kinematic sliminess). From the condition

$$\mathrm{Re} = w \cdot 9.5 \cdot 10^{-3}/(1.142 \cdot 10^{-6}) > 7000.$$

it follows $w > 0.84$ m/s.

With this speed, through one tube of 13.5 × 2.25 mm the liquid circulates with 0.0596 l/s. The number of joined tubes in parallel must be at most 4 and one obtain $w = 0.93$ m/s and $\mathrm{Re} \simeq 7,710$.

Previously, in relation (2.2) there was obtained the thermal flux received by a tube of 1 meter. From the exterior face of the tube to the interior one, the heat is

$$q = \frac{\Delta d_i \cdot \Delta t_i}{10^{-4} + \alpha_i^{-1}}, \tag{2.5}$$

with d_i - the interior diameter of the tube, Δt_i - the mean difference between the temperatures of the faces of the tubes and 10^{-4} m^2·K/W - the thermic resistance of the heat conduction through the wall of tube related to the interior face.

In permanent regime, $q = q_0$. By denoting $\Delta t = \Delta t_i + \Delta t_e$ - the mean difference between the temperature of the gases and of the water from relations (2.2) and (2.5), it follows that $q_0 = \Delta t / D$, where

$$D = \frac{10^{-4} + \alpha_i^{-1}}{\pi d_i} \cdot \frac{e^{rd} + 1}{2\lambda sr(e^{rd} - 1)}.$$

For the warmer zone, according to relation (2.1), it follows:

$$r = \left(\frac{2 \cdot 47.90}{3.36 \cdot 0.05}\right)^{1/2} \simeq 23.88\,\mathrm{m}^{-1}; \quad r_d = 2.388; \quad e^{rd} = 10.89 \quad \text{and} \quad \Delta t = 102\,\mathrm{K}$$

and by applying relation (2.4), one obtains, after calculations, $q_0 \simeq 639.5\,\mathrm{W/m} = 6,395\,\mathrm{W/m^2}$ panel. The length of the panel (that is after assembling the height) for the warmer zone, results that it be $27,102/(2 \cdot 6,395) = 2.12$ m.

For the less warm zone, it follows:

$$r = \sqrt{\frac{2 \cdot 47.90}{3.36 \cdot 0.05}} \simeq 23.32\,\mathrm{m}^{-1}; \quad r_d = 2.332; \quad e^{rd} = 10.30, \quad \Delta t = 76.8\,\mathrm{K}$$

and by applying relation (2.5), one obtains $q_0 = 463.3\,\mathrm{W/m} = 4,633\,\mathrm{W/m^2}$. The length of the less warm zone will be $26,872/(2 \cdot 4,633) = 2.90$ m. The total length will be $2.12 + 2.90 \simeq 5$ m.

The pressure drop determined by the gases flow in the warmer zone is estimated at 20 mm water column and in the second zone at 25 mm water column. The total resulted pressure drop for the gases flow between panels is of 45 mm water column.

3. AN EXAMPLE OF HEAT ECONOMIZER

Each prefab panel includes a tube register in which water flows horizontal through tube groups of 13 × 2.25 mm, linked by vertical tubes of 26 × 3 mm; firstly through 9 groups of 4 tubes each, then through 2 groups of 3 tubes each and finally, through 4 groups of only 2 tubes each, thus ensuring the increase of convection intensity in the interior of tubes as water becomes warm and fights against of salts deposit. On notice in relation (2.4) that through each tubes group flows an water flux of about 0.263 l/s, with velocities of 0.93 m/s through these 9 groups of 4 tubes and also velocities of 1.11 m/s in groups of 3 tubes and of 1.86 m/s in groups of two tubes. The mean values of water temperatures in all three groups are of 33°C, 49°C, and 61°C.

For example, at a total flux of gases of 100,000 m^3/h at 180°C, a volumetric flux (output) of 56,960 m^3n/h results in normal conditions by pressure and temperature (1.013 barr and 0°C). This flux releases the useful output in the heat economizer:

$$Q_T = \frac{56.960 \cdot (1.396 \cdot 180 - 1.384 \cdot 80) \cdot 10^{-3}}{36.000} = 2.31\,\mathrm{MW}$$

saving above 4000 MT/year conventional combustible, without taking into account the amount of CO_2 evolving in atmosphere.

One has observed, according to the relation (2.3), that only one prefab element takes over from gases approximately 53.97 kW, so their number of these will be

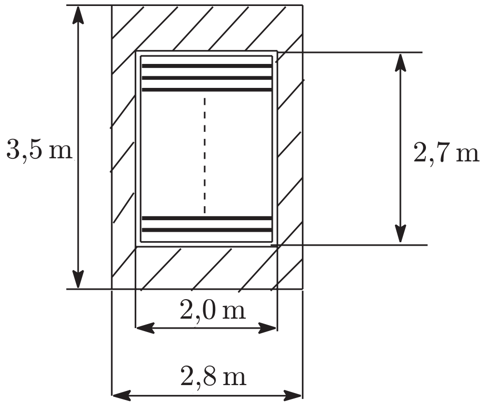
$$n = \frac{2.31 \cdot 10^6}{53.97 \cdot 10^3} = 42 \text{ elements (panels)}.$$

These 42 element-panels of dimensions $5 \times 2 \times 0.05\,\mathrm{m}^3$ each, vertically placed with interspaces of 15 mm. The elements lean on two walls of simple concrete, of 4 cm at each margin, on one base mortar layer. Gases flow in downward sense, from the warm upper head of the heat economizer.

4. CONCLUSIONS

In order to avoid the humectation of the cold zones of the walls of the closing construction, at the interior face of the walls, one provides a first impermeable layer at water. Below and above the elements assembly one assures one free space of about one meter to facilitate the connection of the gases cannular, with the homogenization of their distribution and collection, and also for visiting-control.

The water resulted from condensations (chemically aggressive) will be evacuated after neutralizing. The gases exhaustor, protected at interior against corrosion, will be connected in the downstream of the heat economizer. The connecting tubing of the hot gases at the heat economizer will have a section of minimum 0.6 m^2 and will be isolated at exterior with mineral wool (adequate protected), with thickness of 10 cm.



42×0,05+41×0,015+2×0,01=2,7 m

Figure 2. Transversal section in the heat economizer

The proposed heat economizer composed by connecting more concrete prefab elements (panels) allows the warming of the cooling water of some boilers (for example from 15° to 65°C) with the recovered heat of roast gases (for example usefully cooled from 180° to 80°C). Besides the economy of the fuel recently used for water warming, the thermal pollution is reduced in the area. The recovery of the investment is achieved in at most 4 months.

Editor's note. The recommendations for publication of the two referees of this work share the opinion that the ideas included here can serve possible applications in industry.

REFERENCES

[1] * * * *Manualul inginerului termotehnician*, Editura Tehnică, Bucureşti, 1986.

[2] A. Badea and colab.: *Echipamente şi instalaţi termice*, Editura Tehnică, Bucureşti, 2003.

[3] K. Razajevici: *Tabele şi diagrame termodinamice*, Editura Tehnică, Bucureşti, 1978.

[4] C. Stănăşilă, D. Ştefănoiu, H. Ştefănoiu and O. Stănăşilă: *A recuperative heat exchanger for high temperatures*, Revista de Chimie, Bucureşti, 2009.

[5] R. C. Chaudhary and Arpita Jain: *Combined heat and mass transfer effects on MHD free convection flow past an oscillating plate embedded in porous medium*, Rom. J. Phys., **52**(2007), No. 5-7.

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