TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2015, Vol. 15, No. 1, 51–56

The Influence of a Radiated Heat Exchanger Surface on Heat Transfer

Slawomir Morel*, Jaroslaw Jasinski**, Tadeusz Zloto***, Piotr Stryjewski***

Czestochowa University of Technology
*Industrial Furnaces Division, e-mail: morel@wip.pcz.pl
**Institute of Logistics and International Management
***Institute of Mechanical Technologies, e-mail: zlotot@o2.pl,

Received January 09.2015; accepted January 19.2015

Summary. The experiment lead to establishing the influence of radiated surface development in heat exchangers on the values of heat flux transferred with water flowing through the exchangers placed in an electric furnace chamber. Thread cutting in the form of 0.5 mm and 0.8 mm-deep grooves on pipe heat exchangers of $d = 45$ mm and length 300 mm, resulted in significant increase in heat exchange surface and respectively, depending on groove depth, the increase on heat flux transferred by water by 2 and 1.5 times the values obtained in the case of smooth surface exchangers.

Key words:heat transfer, emissivity of metals, absorptivityof metals.

INTRODUCTION

All formulae defining heat transfer contain a part referring to heat transfer surface area. Increasing effective surface area 'S_{eff}' without changing overall construction size of the heat exchanger is basically achieved by adding fins, needles, grooving or cutting thread form as well as thermal spraying of considerable open porosity and high corrosion resistance coatings.

Surface development methods increase radioactive emission of the walls taking part in heat transfer mainly because in relation to the projection of the walls, their effective surface is many times bigger [10, 11, 12, 16]. Moreover, emission increases as the cavities may be considered to be enclosures whose opening holes in extreme situations have the properties of black bodies, which results from the black bodyphysical model

In practice, while calculating the emission of rough surfaces, one needs to consider the surface tangent to the convexity and the emission coefficient higher than that for smooth surfaces, which considerably increases the stream of heat transferred [1, 3, 15].

BLACK BODY MODEL

Each body has emissivity (e_T) lower than 1. In order to shape an emitting surface of a technical body so that it has the highest possibleemissivity, cavity effect (C) is used. The surface area of the opening hole of a cavity (emission hole S_h) has a considerably higher effective emissivity ($e_{T,ef}$) than the effective surface of the cavity (S_{eff}), marked as (e_T)

The emissivity of a cavity hole ($e_{T,ef}$) increases with the increase of cavity surface ratio 'C_s'(1), fig. 1 [2, 6, 9, 14]:

$$C_s = \frac{S_{eff}}{S_h}, \tag{1}$$

where:
C_s – cavity surface ratio,
S_{eff} – effective cavity surface,
S_h – cavity hole surface.

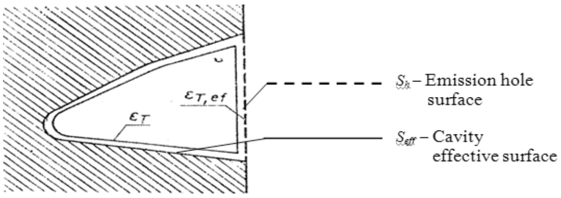


Fig. 1. Black body as an enclosure [12]

Each point of the cavity surface (S_{eff}) should have constant temperature T, constituting the level of emitting surface temperature (S_h).

The emissivity of a cavity hole ($e_{T,ef}$) was presented in figure 2 as a function of cavity surface ratio 'C_s' for different cavity shapes and defined in the form of an equation (2):

$$\varepsilon_{T.ef} = f\left(\varepsilon_T \cdot C_s\right), \tag{2}$$

where:
$e_{T,ef}$ – cavity hole effective emissivity,
e_T – total emissivity,
C_s – cavity surface ratio.

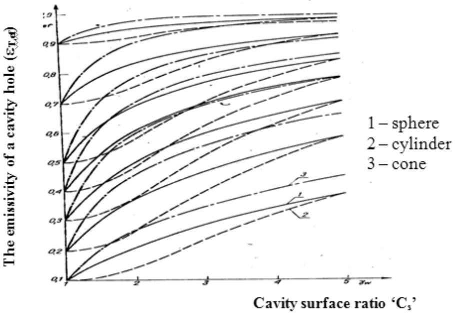


Fig. 2. Emissivity of cavity hole [3]

The dimensions of the cavity should be considerably bigger than the wavelength of the infrared radiation emitted. Negligence of this condition might lead to divergence from thermal radiation laws (Planck's constant, Stefan – Boltzmann law). Moreover, errors in temperature measurement might occur due to the chamber not being isothermaland to other variables influencing temperature.

ABSORPTION AND HEAT EMISSION BY METALS AND NON-METALS

It is generally assumed that metals of pure non-oxidized surface show emissivity ranging from a few hundredths to approximately 0.40. The emissivity of dielectrics is considerably higher and ranges from 0.70 to 0.99. Emissivity ratio $e_T/e_{T,n}$ for metals is higher than 1, whereas for dielectrics it is lower than 1. Monochromatic absorption for metals decreases whereas for non-metals, it increases with the increase of radiation wavelength. If the state of surface bodies does not change, it is generally accepted that the function e_T is temperature-independent. By spraying coatings on metal and non-metal products, emissivity of the surface can considerably be increased for specific exploitation temperature ranges [4, 7, 8].

The increase of the heat absorbed is a function of:

- the value e_T of the coating generated (e_{coat}= 0,70 – 0,95)
- the development of the radiated surface sprayed with a coating, i.e. cavity surface ratio 'C_s'.

Such experimental increase $e_{T,n}$ generated by cavity surface ratio 'C_s' of the coating has been defined with the following formula (3) [8]:

$$\varepsilon_{T,n} = \frac{\varepsilon_{T,n,o}\cdot C_s}{1+(C_s-1)\varepsilon_{T,n,o}} = \frac{\varepsilon_{T,n,o}\sqrt{1+4\left(\frac{R_z}{s}\right)^2}}{1+\left[\sqrt{1+4\left(\frac{R_z}{s}\right)^2}-1-1\right]\varepsilon_{T,n,o}}, \qquad (3)$$

where:

C_s – cavity surface ratio,
R_z– mean roughness,
s – mean roughness interspace,
$e_{T,no}$ – total emissivity in smooth surface normal direction,
$e_{T,o}$– total emissivity to smooth surface half-space.

ABSORPTIVITY AND EMISSIVITY OF METALS

The processes of heat transfer within metals include a thin surface coating of 0 – 10^{-10}m depth. The transfer is induced by the oscillation of atoms and particles present on the surface of a metal unit.

Monochromatic emissivity from a metal surface decreases with the increase of a wavelength (very harmful for infrared radiation). The influence of temperature on the emissivity of metals is scarce. Total emissivity ($e_{T,n}$) increases with temperature, in accordance with Hagen – Ruvens formulae – (equation 4) [8]:

$$\varepsilon_{(\lambda)} = 0,365\sqrt{\frac{\rho T}{\lambda_0}}, \qquad (4)$$

where:

e_λ – monochromatic emissivity to half-space,
ρ – density,
T – temperature,
λ – heat conductivity.

The author of the paper has also established that with the increase of the temperature, reflectivity decreases: the higher cavity surface 'C_s' is, the lower the value of reflectivity.

The presence of an oxidized coating (even one of minimum thickness) on metals considerably increases their heat radiation absorption and emission potential, even in the case of stainless steels. Oxidation time obviously also affects it [5].

ABSORPTIVITY AND EMISSIVITY OF NON-METALS

Numerous results have confirmed that non-metals have considerably higher radiation absorption (l_T) and emission (e_T) potential than metals. Their monochromatic emissivity increases with radiation wavelength, although the increase is not as obvious as in the case of metals [12].

The emissivity of non-metals decreases considerably with the increase of temperature.

White oxides (Mg, Al, Th) have relatively low emissivity in the range of wavelengths from 0 to 5-6 mm, however, for radiation wavelength10 mm, their emissivity has values close to black body radiation.

Coloured oxides (Cr, Ce) have higher emissivity in the range of wavelengths in near infrared than white ones [5].

THE INFLUENCE OF A DEVELOPED EXCHANGER SURFACE ON HEAT RADIATION TRANSFER

Thesis proposed is that developing a heat exchanger surface by e.g. grooving (thread cutting), leads to heat exchange surface increase, which results in the increase of the amount of absorbed heat with unchanged overall dimensions.

The aim of study was to establish the influence of mechanically cut grooves depth (in the shape of an equilateral triangle) on surface development and to verify that developed surface size influences the increase of the heat flux transferred with water flowing through the heat exchanger [13].

The scope of research consisted in comparative studies of the influence of four variants of surface development (same size stainless steel pipes) on the values of transferred heat flux.

The exchangers consisted in: an initial state pipe, a polished pipe, a pipe with 0.5 mm grooving (thread cutting), a pipe with 0.8 mm grooving (thread cutting).

METHODS AND MEASUREMENTS

Measurements were taken usingdevice presented in fig. 3.

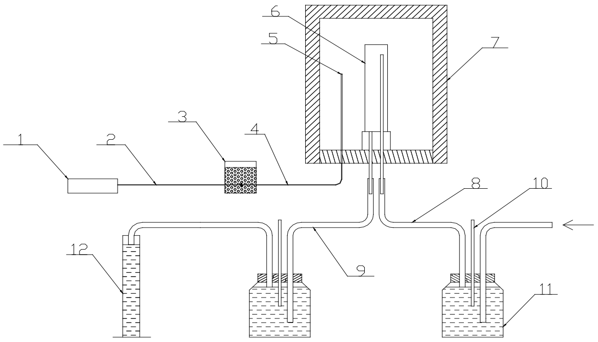


Fig. 3. Device used for the research: 1- DC milivoltmeter V520, 2- copper wires, 3- thermally insulated vessel filled with finely crushed ice, 4- compensating lead, 5- NiAl-NiCr thermocouple, 6- four steel pipes of the same overall dimensions l=300mm, 7- furnace, 8- water inlet pipe, 9- water outlet pipe, 10- thermometers, 11- hermetic vessels, with thermometers placed inside, 12- beaker for water flow rate measurement

An exchanger water inlet pipe and outlet pipe was placed in a furnace. In the furnace door, NiAl-NiCr thermocouple connected to DC milivoltmeter with compensating leads was inserted. Thermocouple cold junction was placed in a thermally insulated vessel (vacuum flask) filled with finely crushed ice with distilled water poured over it, which ensured reference temperature of 0°C.Thermometers were placed in two hermetic glass vessels with a precise temperature reading function; one measuring inlet water temperature, with the range of 0-30°C, the other one measuring outlet water temperature, with the range of 0-50°C. The thermometers were placed at around 1-meter distance from the heat source, which ensured the protection from indication errors. All parts of the water unit were connected with rubber pipes of *d*= 10 mm. The value of water flow intensity was measured by filling a laboratory beaker of 1 dm³ capacity and measuring filling time. Temperature inside furnace chamber was read from the NiAl-NiCr thermocouple.The temperature was taken by means of stationary temperature increase measurement with a fixed water flow intensity.The experiment was carried out in four stages.In the first stage an initial state stainless steel pipe of *d*= 45.25 mm and *l* = 300 mm was used while in the second stage a stainless steel polished pipe of the same dimensions.

The stages mentioned above started after the furnace chamber had been heated. Water inflow and outflow temperatures were constantly being measured with mercurial thermometers. The temperature inside the furnace of 700°C was being constantly monitored with thermocouple. The measurements were read every 60 minutes and repeated 6 times, which was assumed sufficient due to high repetitiveness. In all the stages the measurements were taken exactly in the same way, with attempts to keep the same water flow intensity.

RESULTS AND ANALYSIS

For further calculations pipes developed surface calculation.

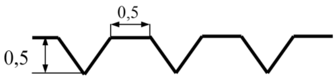
- Initial state pipe *d* = 45.25 mm, *l* = 300 mm

$$S = \pi \cdot d \cdot l = 3{,}14 \cdot 45{,}25 \cdot 300 = 42625{,}5 \quad mm^2 = 0{,}0426 \quad m^2.$$

- Polished pipe *d* = 45.10 mm, *l* = 300 mm

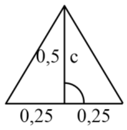
$$S = \pi \cdot d \cdot l = 3{,}14 \cdot 45{,}10 \cdot 300 = 42484{,}2 \quad mm^2 = 0{,}0425 \quad m^2.$$

A pipe with 0.5 mm grooving:



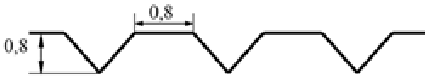
n_g – number of grooves = 284.

In an equilateral triangle, the altitude perpendicular to the line containing the base, divides the base into two equal parts. Therefore, it can be determined using the Pythagorean theorem that the hypotenuse c = 0.54:



$$S = (2 \cdot c + 0{,}5) \cdot l \cdot n_g = (2 \cdot 0{,}54 + 0{,}5) \cdot 300 \cdot 284 = 134616 \quad mm^2 = 0{,}1346 \quad m^2.$$

A pipe with 0.8 mm grooving:



n_g – number of grooves = 168,

$$S = (2 \cdot c + 0{,}8) \cdot l \cdot n_g = (2 \cdot 0{,}89 + 0{,}8) \cdot 300 \cdot 168 = 130032 \quad mm^2 = 0{,}1300 \quad m^2.$$

STAGE I RESULTS

In stage I an initial state pipe of d = 45.25 mm was used as an exchanger. The results obtained are presented in table 1 and figure 4. The values presented in the table were obtained by repeating the measurement 6 times.

STAGE I ANALYSIS

Mean inflow water temperature was 12.2°C, the heat transfer area was 42625.5 mm², the exchanger was placed in a furnace with the temperature of 700°C. After the water had flown through the exchanger, mean water temperature increased to 29°C. Mean water flow intensity was 0.033 m³/h. The heat flux absorbed by water was determined at 2.196 kW.

STAGE II RESULTS

In stage II a polished pipe of *d* = 45.10 mm was used. Also in this stage, measurements were taken 6 times. The results are presented in table 2 and in fig. 4. Similarly to stage I, the same measurement facility was used.

STAGE II ANALYSIS

In the case of a polished pipe used as an exchanger (in stage II), the following results were obtained:

- mean inflow and outflow water temperature difference was: 15.4°C,
- drop of mean temperature difference as compared with stage I was 1.4°C,
- water flow intensity: 0.033 m³/h,
- temperature inside the furnace: 700°C,
- mean heat flux value: 2.151 kW.

With the use of a polished pipe, a drop in the value of transferred heat flux by approx. 2% as compared to the use of an initial state pipe occurred. The result obtained justifies the decrease of radiated heat transfer surface area by 141.3 mm² and the increase of the potential to reflect heat radiation due to pipe polishing.

STAGE III RESULTS

The results of stage III of the experiment, with the use of a pipe with 0.5 mm grooving, are shown in table 3 and graphically presented in fig. 4. The values were obtained in measurements taken at 60-minute intervals with a furnace used as a heat source of 700°C.

STAGE III ANALYSIS

Mean water temperature of 12.1°C was determined at the inflow to the pipe with 284 grooves cut in the shape of equilateral triangles, with a side length of 0.54 mm and the base of 0.5 mm. The temperature measured at the outflow was 30.6°C. Water flow intensity was 0.057 m³/h. The heat absorbed by the water was determined at 4.195 kW. Thus, as compared to the initial state pipe, the heat flux increased by 2 kW. Therefore, the heat flux transferred by water increased by 92% as compared with the value obtained in the case of initial state pipe. The above-mentioned phenomenon can be justified with the increase of heat transfer surface area by approx. 215% as compared with initial state pipe and the occurrence of cavity effect – the increase in the degree of emissivity of the radiated surface, which lead to such a considerable increase in the transferred heat flux.

Table 1. Results of experiment the first stage

The state of exchanger surface	Temperature [°C]		Water flow [m³/h]	Heat flux transferred with water Q [kW]
	Inflow	Outflow		
Initial state pipe	11,8	27,8	0,036	2,262
	12,3	29,4	0,033	2,196
	12,3	29,4	0,033	2,196
	12,2	29,3	0,032	2,197
	12,2	29,1	0,032	2,169
	12,1	28,9	0,032	2,155

Table 2. Results second stage experiment

The state of exchanger surface	Temperature [°C]		Water flow [m³/h]	Heat flux transferred with water Q [kW]
	Inflow	Outflow		
Polishedpipe	11,4	26,6	0,035	2,163
	11,7	27,0	0,033	2,064
	13,2	28,9	0,033	2,208
	13,2	28,8	0,032	2,133
	12,2	27,4	0,032	2,162
	12,3	27,6	0,032	2,177

Table 3. Results of third stage experiment

The state of exchanger surface	Temperature [°C]		Water flow [m³/h]	Heat flux transferred with water Q [kW]
	Inflow	Outflow		
The pipe with 0.5 mm grooving	12,8	30,7	0,060	4,243
	12,8	30,8	0,060	4,268
	12,6	30,7	0,056	4,009
	11,8	29,5	0,057	3,978
	11,1	30,6	0,055	4,256
	11,1	31,3	0,055	4,418

STAGE IV RESULTS

In stage IV a pipe with 0.8 mm grooving was used, with the total of 168 grooves cut. Similarly to stage I, II, III, measurements were taken 6 times, with the use of a furnace with the temperature of 700°C, monitored with a milivoltmeter. The results are shown in table 4 and fig. 4.

STAGE IV ANALYSIS

Analogically to stages I, II and III, the following values were obtained:

- inflow water temperature: 13.9°C,
- outflow water temperature: 30.5°C,
- drop of mean temperature difference as compared to stage III: 3.6°C,
- heat exchange surface area: 130032 mm^2,
- water flow: 0.060 m^3/h,
- heat flux absorbed by water: 3.506 kW; as compared with initial state pipe: increase by 1.312 kW (approx. 60%).

Comparing the value of the heat flux absorbed with the results obtained in stage III, stage IV features a 16% drop approx. This is mainly due to the decrease in heat exchange surface area as compared with the pipe with 0.5 mm grooving (used in stage III).

The measurements of heat transfer values with the use of four exchangers, differing by the state of surface development, made it possible to determine the influence of surface state on the values of heat flux absorbed by water.

Heat exchange surface area was respectively: initial state pipe: 4.262 dm^2, heat flux: 2.20 kW; polished pipe: 4.248 dm^2, heat flux: 2.15 kW; pipe with 0.5 mm grooving: 13.461 dm^2, heat flux: 4.20 kW; pipe with 0.8 mm grooving: 13.003 dm^2, heat flux: 3.50 kW

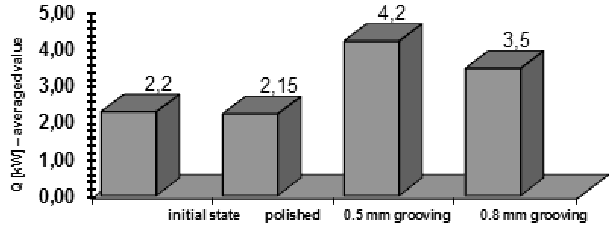


Fig. 4. Heat flux transferred by the four types of exchangers

CONCLUSIONS

The lowest value of absorbed heat flux was determined with the use of a polished pipe as a heat exchanger. With a slight development of initial state pipe surface, namely polishing, a drop in heat transfer by 2% was obtained. As it has already been mentioned, the drop occurred due to the decrease in heat exchange surface by 0.014 dm^2 and the increase in heat radiation reflectivity resulting from pipe polishing. In stage III a pipe with 0.5 mm grooving was used. As a result of cutting 284 grooves, the radiated surface of the pipe (exchanger) increased by approx. 215%, which lead to doubling the heat flux absorbed by water flowing through this pipe. The values obtained clearly confirm the vital influence of surface development on heat transfer, which makes such a procedure worthwhile. In the case of a pipe with 0.8 mm grooving, the developed surface decreased as compared with stage III of the experiment by approx. 15%. Transferred heat flux decreased by approx. 16%.

In conclusion, heat exchange surface development by cutting a particular number of grooves of particular depth may lead to the increase in the amount of heat absorbed by as much as 100%.

Further research should be carried out, with spraying the pipes used in the experiment with coatings of high absorptivity (high emissivity, high cavity surface ratio '*Cs*') and high thermal conductivity. Based on the results and statements already established, an experiment should be carried out in industrial conditions, with the use of a heat exchanger with a coating sprayed ($\lambda = 40 W/mK$) on the thread cutting on a cast iron recuperator, Field unit or a radiating pipe.

REFERENCES

1. **AbrgmowiczB.G., Goldsztein W.Ł., 1977:**Intienisifikacjatiepłobmiena izłuczeniem s pomoszczju pokrytej. Eniergia, Moskwa, 26-39.
2. **Bielański J., 1974:** Chemia Nieorganiczna. WNT, Warszawa.
3. **Burakowski T., Wierzchoń T., 1995:** Inżynieria powierzchni metali. WNT, Warszawa.
4. **Hernas A., Dobrzański J., 2003:** Trwałość i niszczenie elementów kotłów i turbin parowych. Wyd. Politechniki Śląskiej, 24-45.

Table 4. Results of experiment the fourth stage

The state of exchanger surface	Temperature [°C]		Water flow [m^3/h]	Heat flux transferred with water Q [kW]
	Inflow	Outflow		
The pipe with 0.8 mm grooving	13,8	30,7	0,058	3,515
	13,8	30,8	0,060	3,583
	13,9	30,7	0,061	3,567
	14,0	29,5	0,060	3,508
	14,0	30,6	0,061	3,458
	14,1	30,7	0,061	3,407

5. **Hovis J., 2006:** Low NO burners for metallurgical furnaces Iron a. Steel Eng T 63 nr 6, 43 – 46.
6. **Morel S.:** Raport z realizacji projektu badawczego nr 6 0482 91 01. Prace niepublikowane Politechnika Częstochowska Katedra Pieców Przemysłowych.
7. **Morel S., 2009:** Zastosowanie powłok natryskiwanych plazmowo w gospodarce cieplnej huty. Przegląd Spawalnictwa, R.81 nr 9, 90-93.
8. **Morel S., 2011:** Application of Plasma-Sprayed Coatings in Heat Absorption by Radiated Walls. Archive of Energetics / Archiwum Energetyki T.41 nr 3-4, 111-126.
9. **Morel S., 2011:** Zastosowanie powłok plazmowych w hutniczych urządzeniach grzewczych. Hutnik-Wiadomości Hutnicze R.78 nr 5, 449-451.
10. **Morel S., Jasiński J., Jasiński J., Jeziorski L., 2012:** Powłoki natryskiwane plazmowo na elementach urządzeń do fluidalnej obróbki cieplnej. Inżynieria Materiałowa R.33 nr 5 (189), 456-459.
11. **Morel S., 2012:** Powłoki natryskiwane plazmowo dla potrzeb gospodarki. Mechanik nr 8-9, 783-785.
12. **Morel S., 2012:** Koszty wytwarzania powłok metodami natryskiwania cieplnego. Przegląd Spawalnictwa R.84 nr 8, 7-10.
13. **Nava J.C., 2009:** Cost-effective thermal spray coatings for the boiler industry. Welding Journal No 7, Vol. 99.
14. **SalaA., 1982:** Radiacyjna wymiana ciepła. WNT, Warszawa, 18-43.
15. **Węgrzyn T., Piwnik J., 2012:** Low alloy welding with macrojet cooling. Archives of Metallurgy and Materials vol. 57.
16. **Zubielewicz M., 2006:** Kierunki badań i rozwoju powłok ochronnych. Ochronaprzedkorozją, nr 4, 97-98.

ROZWINIĘCIE OPROMIENIOWANEJ POWIERZCHNI WYMIENNIKA CIEPŁA

Streszczenie. Ustalono wpływ stanu rozwinięcia opromieniowanej powierzchni wymienników ciepła na wartości strumienia ciepła unoszonego z wodą przepływającą przez wymienniki umieszczone w komorze pieca elektrycznego. Nacięcie rowków o głębokości 0,5 i 0,8 mm na obwodzie rurowych wymienników ciepła o średnicy 45 mm i długości 300 mm spowodowało ponad dwukrotny wzrost powierzchni wymiany ciepła i odpowiednio w zależności od głębokości rowków około 2 i 1,5 krotny wzrost strumienia ciepła unoszonego z wodą względem wartości uzyskanych w wymiennikach o gładkich powierzchniach.

Słowa kluczowe: przepływ ciepła, emisja promieniowania przez metale, absorpcja promieniowania przez metale.