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P.K. KRAJEWSKI*, A. GRADOWSKI*, W.K. KRAJEWSKI*

HEAT EXCHANGE IN THE SYSTEM MOULD – RISER – AMBIENT. PART II: SURFACE HEAT EMISSION FROM OPEN RISER TO AMBIENT

WYMIANA CIEPŁA W UKŁADZIE FORMA – NADLEW-OTOCZENIE. CZĘŚĆ II: WSPÓŁCZYNNIK EMISJI CIEPŁA Z OTWARTEGO NADLEWU DO OTOCZENIA

The subject of the paper is heat exchange in the system casting – riser – ambient. The examinations were focused on evaluating temperature dependence of the coefficient of heat exchange from open (not shielded) top surface of riser to ambient. The examinations were carried out on the open surface of cast steel riser, of temperatures 1000-1500°C. On the basis of the performed examinations it was stated that heat emission coefficient changes its mean values by about 50% during feeding process of the mild steel casting, i.e. from about 0.28 in liquid state to about 0.42 at temperatures close to solidus. This wide range of surface heat emissivity changes should be taken into account when boundary conditions are formulated in elaborated models of solidification and in designing risering systems.

Keywords: Castings, Risers, Surface heat emission, Heat balance, Solidification modelling

Przedmiotem artykułu jest wymiana ciepła w systemie odlew – nadlew – otoczenie. Celem badan było wyznaczenie temperaturowej zależności współczynnika wymiany ciepła z odkrytej, nieizolowanej powierzchni nadlewu do otoczenia. Badania wykonano dla odlewu staliwnego z odkrytym nadlewem, dla zakresu temperatury powierzchni nadlewu 1000-1500°C. Na podstawie wykonanych badań stwierdzono, iż współczynnik emisji ciepła z nieizolowanej powierzchni nadlewu do otoczenia zmienia swą wartość w badanym zakresie temperatury o około 50%, tj. od około 0.26 – 0.30 dla metalu w stanie ciekłym do około 0.42 – 0.46 dla metalu w stanie stałym, w pobliżu temperatury solidus. Powyższy szeroki zakres zmian emisyjności powinien być uwzględniany w budowanym modelach symulacji procesu krzepnięcia i projektowania systemów zasilania krzepnących odlewów.

List of abbreviations and symbols in the paper

α_{AMB} – coefficient of heat exchchange from open riser surface to ambient, W/(m^{2}K)
$\alpha_{P.AMB}$ – coefficient of heat exchchange from plate surface to ambient, W/(m^{2}K)
$\alpha_{P.rad.AMB}$ – coefficient of heat exchchange by radiation from plate surface to ambient, W/(m^{2}K)
$\alpha_{P.conv.AMB}$ – coefficient of heat exchchange by convection from plate surface to ambient, W/(m^{2}K)
dQ – infinitesimal heat quantity, J
d – differential
acc, accumulation
conv, convection
rad, radiation
AMB, ambient
P or PLATE, accumulating plate
R-P, – riser - plate
$dQ_{P\cdot acc}$ – heat accumulated by the accumulating plate, J
$dQ_{P.AMB}$ – total heat emitted from external plate surface to ambient, J
$dQ_{P.rad.AMB}$ – heat emitted by radiation from external plate surface to ambient, J
$dQ_{P.conv.AMB}$ – heat emitted by convection from external plate surface to ambient, J
V_p – volume of the accumulating plate, m^3

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF FOUNDRY ENGINEERING, 23 REYMONTA STR., 30-059 KRAKOW, POLAND

A_p – cooling surface of the accumulating plate, m^2
ρ_p – mass density of the accumulating plate material, kg/m^3
C_p – heat capacity of the accumulating plate material, J/(kg K)
X_P – thickness of accumulating plate, m
T_{AMB} – temperature of ambient, K
T_{PLATE} – temperature of accumulating plate, K
T_{RISER} – temperature of the riser top surface A_P, K
ϑ_{PLATE} – relative temperature of accumulating plate surface A_P, K
σ_o – black body radiation coefficient, $5.67*10^{-8}$,$W/(m^2K^4)$
ε – surface emissivity coefficient
ε_P – surface emissivity coefficient from the accumulating plate to ambient
ε_{R-P} – total emissivity coefficient between surfaces of accumulating plate and riser
ε_R – surface emissivity coefficient from the open mild steel riser to ambient
τ – time, s
Nu, Gr and Pr – Nusselt, Grashof and Prandtl numbers
L – linear dimension of accumulating plate, m
β_{AIR} – volume expansion of air, 1/K
λ_{AIR} – thermal conductivity of air, W/(m K)
ν_{AIR} – kinematic viscosity of air, m^2/s
C_{AIR} – heat capacity of air, J/(kg K)
g – gravity, 9.81 m/s^2
C, n – coefficients in Formulas (11) and (13)

1. Introduction

The amount of heat transferred from risers to ambient is of a significant value in the overall heat balance. In foundry practice, shape castings or ingots solidify in many cases with not shielded top surfaces of their open risers or ingot-heads.

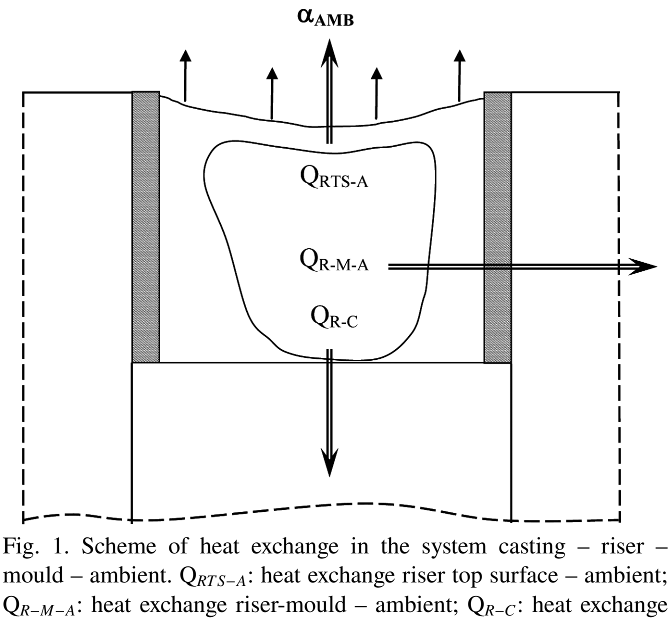

Fig. 1. Scheme of heat exchange in the system casting – riser – mould – ambient. Q_{RTS-A}: heat exchange riser top surface – ambient; Q_{R-M-A}: heat exchange riser-mould – ambient; Q_{R-C}: heat exchange riser – casting

Simulation of the solidification processes [1] requires knowledge of several boundary parameters, among others, the coefficient of heat transfer to the ambient from the mentioned above metal surfaces as well as from outer moulds surfaces. The top surface of a riser emits heat to ambient via radiation, convection and conduction – Fig. 1. The coefficient of heat transfer, here denoted as α_{AMB}, describes sum of the heat transferred via radiation and convection, while conduction is assumed to be negligible [2-4]. The value of the $\alpha_{eff.AMB}$ influences, among others, the solidification process of risers and castings, especially the feeding process. The feeding process depends on grain-size of the casting, which can be controlled by heterogeneous nucleation, or by the intensity of cooling, e.g. [5-9], which depends also on the α_{AMB} value.

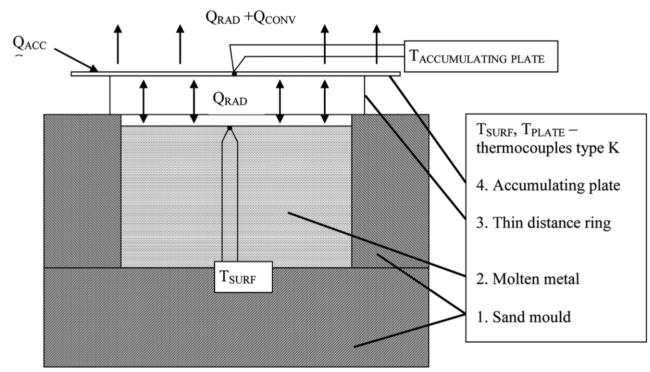

Fig. 2. Scheme of the laboratory stand used during the examinations of the " ε_R" heat emissivity coefficient [10]

The laboratory stand used during the examinations, shown in Fig. 2, consists of sand mould (1) filled-in with metal (2), thin distance ring of stainless steel (3) and pure Al accumulating plate of known thermo-physical properties (4). The investigations are aimed at determining coefficient of thermal exchange in the system: non-shielded top surface of riser or one shielded with an insulating material (e.g. powdered sand mass) – ambient. These are coefficients of heat emissivity ε and α_{AMB}. Details of the α_{AMB} coefficient for outer surfaces of the sand-shield of a given density are presented in Ref. [10], while the present part is aimed at determining the heat emissivity coefficient from open top surface of a riser to ambient.

During the experiments the following materials were used:

– silica-quartz sand mould poured with mild steel (T_{liq} – T_{sol} range ~1510-1460°C),

– accumulating plate made from pure Al of thickness 1.4 mm, density 2700 kg/m^3, mean heat capacity 1025 J/(kgK), oxidized in air at 600°C

The heat balance of the system: heat radiating surface – accumulating plate – ambient, is as follows:

$$dQ_{R-P.rad} = dQ_{P.acc} + dQ_{P.AMB} \quad (1)$$

$$dQ_{P.AMB} = dQ_{P.rad.AMB} + dQ_{P.conv.AMB} \quad (2)$$

$$dQ_{P.acc} = X_P A_P \rho_P c_P \;\; d(T_{PLATE} - T_{AMB}) = V_P \rho_P c_P \;\; d\vartheta_{PLATE}$$

$$\vartheta_{PLATE} = (T_{PLATE} - T_{AMB}) \quad (3)$$

$$dQ_{P.rad.AMB} = \sigma_0 \varepsilon_P (T^4_{PLATE} - T^4_{AMB}) A_P \;\; d\tau \quad (4)$$

$$dQ_{P.conv.AMB} = \alpha_{P.conv.AMB} \left(T_{PLATE} - T_{AMB}\right) A_P \;\; d\tau \quad (5)$$

$$dQ_{P.AMB} = \alpha_{P.AMB} \vartheta_{PLATE} A_P \;\; d\tau \quad (6)$$

The $\alpha_{P \cdot AMB}$ coefficient consist of the convection part ($\alpha_{P.conv.AMB}$) and the radiation part ($\alpha_{P.rad.AMB}$), i.e.:

$$\alpha_{P.AMB} = \alpha_{P.conv.AMB} + \sigma_0 \varepsilon_P \frac{T^4_{PLATE} - T^4_{AMB}}{T_{PLATE} - T_{AMB}} \quad (7)$$

On the other hand we have:

$$\alpha_{P.AMB} A_P \vartheta_{PLATE} d\tau = -V_P \rho_P C_P d\vartheta_{PLATE} \quad (8)$$

from which:

$$\alpha_{P.AMB} = \frac{-V_P \rho_P C_P}{A_P \vartheta_{PLATE}} \frac{d\vartheta_{PLATE}}{d\tau} \quad (9)$$

Heat radiation between riser surface and accumulating plate is described by

$$dQ_{R-P.rad} = \varepsilon_{R-P} \sigma_0 \left(T^4_{RISER} - T^4_{PLATE}\right) A d\tau$$

$$where \quad \frac{1}{\varepsilon_{R-P}} = \frac{1}{\varepsilon_R} + \frac{1}{\varepsilon_P} - 1 \quad (10)$$

Combining Formulas (1), (3), (6) and (10) one can obtain the following relationship:

$$\varepsilon_R = \frac{1}{\dfrac{\sigma_0 (T^4_{RISER} - T^4_{PLATE})}{X_P \rho_P c_P \;\; \dfrac{dT_{PLATE}}{d\tau} + \alpha_{P.AMB} \left(T_{PLATE} - T_{AMB}\right)} - \dfrac{\sigma_0}{(\alpha_{P.AMB} - \alpha_{P.conv.AMB})} \dfrac{(T^4_{PLATE} - T^4_{AMB})}{(T_{PLATE} - T_{AMB})} + 1} \quad (11)$$

Calculating coefficient of heat emission from accumulating plate to ambient can be made from the following relationship:

$$Nu = C \left(Gr \cdot Pr\right)^n \quad (11)$$

where:

$$Nu = \frac{\alpha_{P.conv.AMB}}{\lambda_{AIR}} L; \qquad Gr = \frac{\beta \;\; \Delta T \;\; g \;\; L^3}{\nu^2_{AIR}}; \qquad Pr = \frac{\nu_{AIR}}{a_{AIR}} \quad (12)$$

taking C=0.54 and n=0.25 for the expected value $Gr \cdot Pr \leqslant 2000$ one can obtain after rearranging the following relationship:

$$\alpha_{P.conv.AMB} = 0.54 \lambda_{AIR} \left(\frac{\beta_{AIR} \;\; \Delta T \;\; g \;\; L^3}{\nu^2_{AIR}}\right)^{0.25} L^{-0.25} \quad (13)$$

and finally heat emissivity from external surface of plate to ambient can be calculated from:

$$\varepsilon_P = \frac{\left(\alpha_{P.AMB} - \alpha_{P.conv.AMB}\right)\left(T_{PLATE} - T_{AMB}\right)}{\sigma_0 \left(T^4_{PLATE} - T^4_{AMB}\right)} \quad (14)$$

2. Results and discussion

The results of the performed examinations are shown in Figs 3-5. From Fig. 3 it can be seen, that the relationship $\alpha_{P.AMB}$ *vs. surface temperature* of the accumulating Al plate can be described by a polynomial of 3rd degree with high accuracy R^2 of about 98%. Furthermore, it appears from Fig. 4, that thermo-physical properties of air can be also described with simple polynomial relationships, which allows simplifying the following calculations of $\alpha_{P.AMB}$ coefficient of the accumating plate.

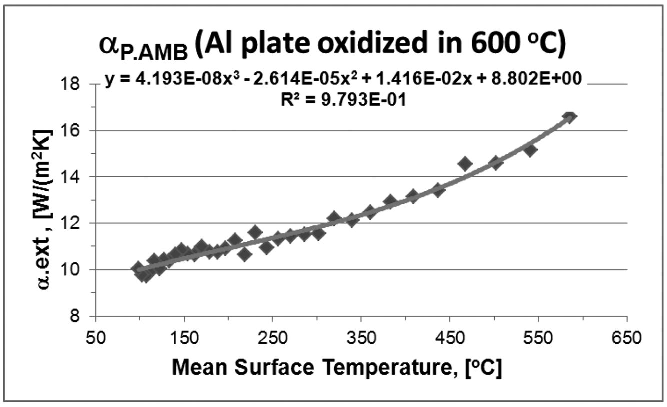

Fig. 3. Exemplary temperature dependence of the $\alpha_{P.AMB}$ coefficient obtained for pure Al plate oxidized in air at temperature of 600°C

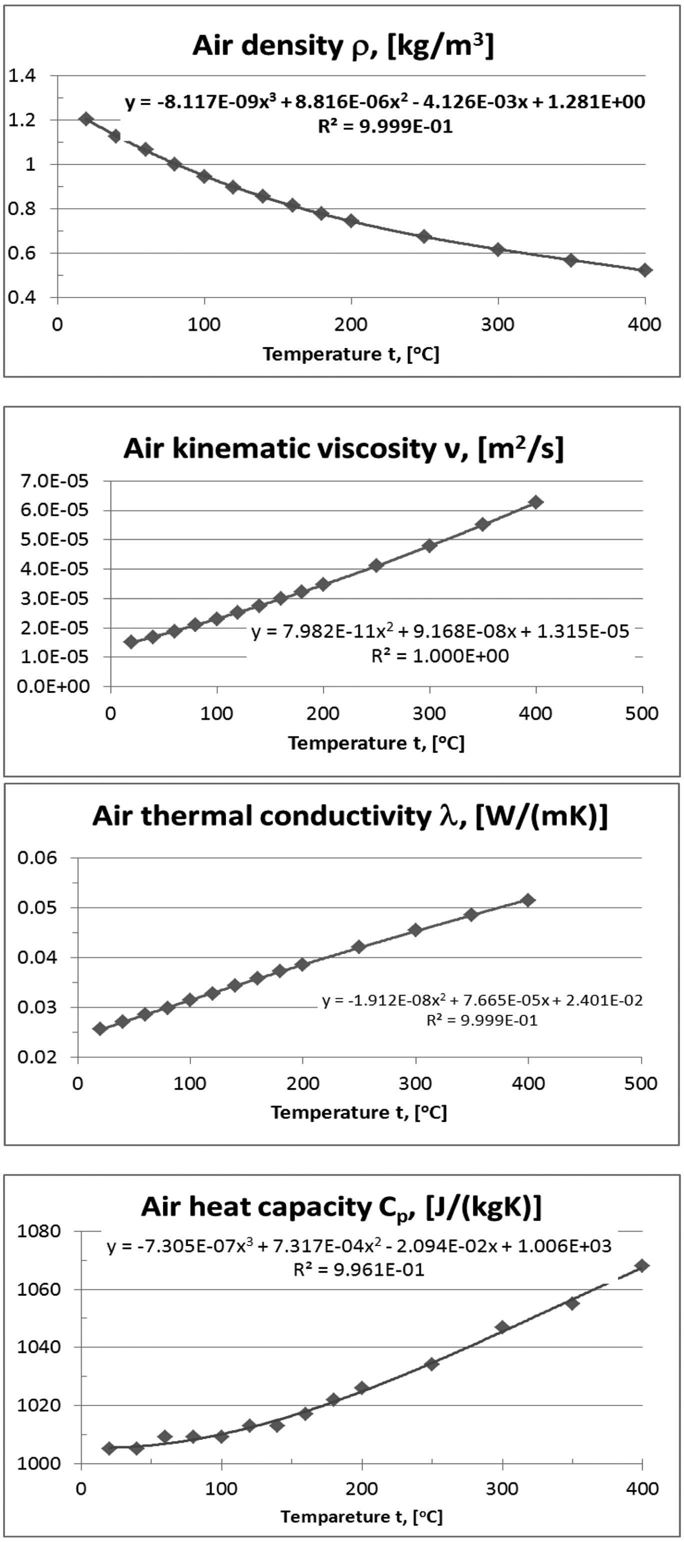

Fig. 4. Termo-physical properties of air vs. temperature (Diagrams based on data published in [11])

3. Results and discussion

The results of the performed examinations and calculations are shown in Fig. 5. From Fig. 5 it can be seen, that the relationship: *heat emissivity vs. surface temperature* is not simple. Namely, it takes values about 0.26-0.3 in intial stage of solidification, shortly after mould pouring. Then, within temperature range liquidus – solidus the emmisivity increases, reaching near solidus temperature its maximal values, 0.42 – 0.46. However, in lower temperatures in the solid state, it gradually decreases, and at temperature about 1000°C takes value about 0.32 – 0.35.

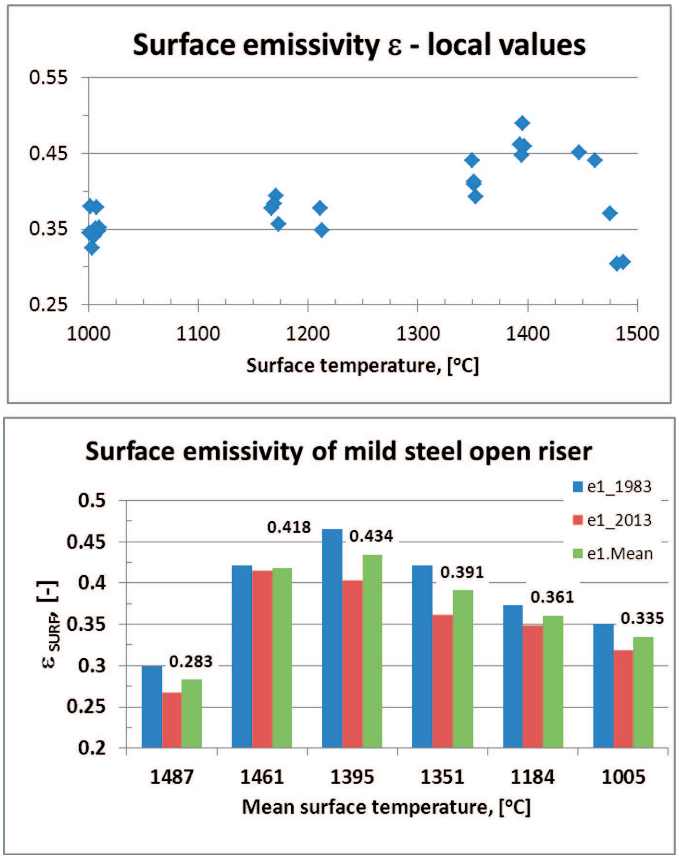

Fig. 5. Coefficient of surface heat emission from non-shielded open cast steel riser

TABLE 1

Values of mean surface emissivity vs. surface temperatures for mild steel open riser

Range of surface temperature [°C]	Mean surface temperature [°C]	Mean surface emissivity
1480 - 1496	1487	0.283
1440 - 1480	1461	0.418
1392 - 1398	1395	0.434
1350 - 1354	1351	0.391
1167 - 1214	1184	0.361
1001 - 1010	1005	0.335

Summing up, the results obtained showed, that there is need to take into consideration the relationship *heat emissivity vs. temperature*, because it changes its values by about 50% during the feeding process. The evaluated heat emissivity coefficient in temperatures close to liquidus takes value of about 0.283, which is very close to 0.28 value reported in literature for mild molten steel [12]. In lower temperatures, close to solidus, surface heat emissivity increases and then slowly decreases – Table 1. The presented here simple measure method allows obtaining parameters of heat emission from the risers surfaces to ambient, however detailed investigations are needed for individual systems. It should be noted that taking a mean value of surface emissivity for the whole temperature range of the solidifying riser can lead to surplus inaccuracy of calculating the feeding systems of castings. Finally, the values obtained in the presented examinations allow to formulate boundary conditions for the computer-aided simulation of the processes of heat and mass transfer in the system mild steel casting riser – ambient [11-12].

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