ARCHIVES OF METALLURGY AND MATERIALS
Volume 53 2008 Issue 3

M. GÓRSKA*, L. SZECÓWKA*, R. BUDZIK*

CONVECTIVE HEAT EXCHANGE DURING FLOW AROUND THE HORIZONTAL CYLINDER WITH A HOT COMBUSTION GAS STREAM DISTURBED BY PULSATIONS

KONWEKCYJNA WYMIANA CIEPŁA PODCZAS OPŁYWU WALCA ZABURZONYM PULSACYJNIE STRUMIENIEM SPALIN

The paper results of experimental research of convective heat transfer during flow of disturbance hot combustion gas around the horizontal cylinder was presented. Measurements conducted at non-disturbance and pulsation disturbance flow of combustion gas. The air stream supply to burner submit disturbance with frequency definite. Convective heat transfer process determine by used special measuring cylinder with applicable additional instrumentations. Experimental tests were carried out on a properly designed measurement cylinder furnished with a number of thermocouples embedded along the cylinder perimeter. The cylinder was placed horizontally in a heating chamber equipped with an axially positioned gas burner fired with natural gas. The measurement region was selected beyond he zone of the greatest non-uniformities of temperature and velocity fields in the heating chamber cross-section, and the disturbances that occurred in this region were generated using a pulsator positioned in the path of primary air feeding to the burner. The experimental tests were conducted in the temperature range of flowing combustion gas from 250 to 750°C and with the introduction of pulsatory disturbances of a frequency in the range from 14 to 74 Hz. Experimental tests performed with the undisturbed flow were taken as a baseline. The results obtained from the experiment carried out enabled the calculation of the Nu number on the cylinder perimeter and represent it is a function or the frequency of introduced pulsatory disturbances. The experimental tests carried out have shown an increase in the Nu number at the inflow front in an angle of 0o and in the rear part in an angle of 180°, and a slight decrease at the wall boundary layer detachment point in an angle from 90° to 110°.

Podczas prowadzenia prac nad konwekcyjną wymianą ciepła podczas opływu zaburzonym pulsacyjnie strumieniem płynu zauważono zdecydowany brak publikacji przedstawiających wyniki badań opływu zimnego walca gorącym strumieniem płynu zaburzonego pulsacjami. Badania eksperymentalne wykonano na odpowiednio zaprojektowanym walcu pomiarowym, wyposażonym w szereg termoelementów zatopionych na obwodzie walca. Walec wykonano ze stali nierdzewnej o znanym współczynniku przewodzenia ciepła, który chłodzono od wewnętrznej strony poprzez układ chłodzenia wodnego. Walec umieszczono poziomo w komorze grzewczej wyposażonej w umieszczony osiowo palnik gazowy opalany gazem ziemnym. Regulacje dopływu gazu i powietrza wykonywano przy użyciu zaworów, opierając się o dane z analizatora spalin. Obszar pomiarowy wybrano poza strefą największych nierównomierności pola temperatury i prędkości w przekroju poprzecznym komory grzewczej, a zaburzenia jakie w tym obszarze występowały generowano przy użyciu pulsatora umieszczonego na drodze podawania powietrza pierwotnego do palinka. Opracowano specjalny rodzaj generatora pulsacji, który podczas podawania oscylacyjnego powietrza do palnika nie powodował zgaszenia płomienia w komorze. Częstotliwość pulsacji regulowano za pomocą falownika tyrystorowego. Podczas prowadzenia badań eksperymentalnych w podwyższonych temperaturach, głównym problemem stało się promieniowanie cieplne spalin i ścian komory, które uniemożliwiało prawidłowe wyznaczenie lokalnego współczynnika wnikania ciepła na obwodzie walca. Problem ten rozwiązano przez zastosowanie próżniowego przyrządu do pomiaru strumienia ciepła dostarczanego na drodze promieniowania. Odpowiednio zaprojektowana konstrukcja przyrządu pozwalała na dobór głowicy przyrządu o identycznym współczynniku emisyjności co pozwalało na jego pominięcie w dalszych obliczeniach. Zastosowanie tego przyrządu pozwoliło wyodrębnić z całkowitego strumienia ciepła dostarczanego do powierzchni walca radiacyjny strumień ciepła. Po zastosowaniu tego cyklu obliczeniowego uzyskano strumień ciepła dostarczany jedynie drogą konwekcyjnej wymiany ciepła.

Opracowana metodyka pozwalała na wyodrębnienie konwekcyjnej wymiany ciepła niezależnie od temperatury przepływającego gazu i temperatury ścian komory grzewczej. Badania eksperymentalne prowadzono w zakresie temperatur przepływających spalin 250÷750°C oraz przy wprowadzaniu zaburzeń pulsacyjnych o częstotliwości z zakresu 14÷74 Hz. Jako punkt odniesienia traktowano badania eksperymentalne wykonane przy przepływie niezaburzonym. Wyniki uzyskane podczas prowadzonego eksperymentu pozwoliły na obliczenie lokalnej liczby Nu na obwodzie walca i przedstawienie w funkcji częstotliwości wprowadzanych zaburzeń pulsacyjnych, temperatury spalin oraz liczby Re.

---

* FACULTY OF MATERIALS PROCESSING TECHNOLOGY AND APPLIED PHYSICS, INSTITUTE OF PHYSICS, CZĘSTOCHOWA UNIVERSITY OF TECHNOLOGY, 42-200 CZĘSTOCHOWA, 19 ARMII KRAJOWEJ AV., POLAND

Wprowadzenie pulsacji w przepływ spalin zapewnia ich właściwą cyrkulację, co zasadniczo polepsza warunki wymiany ciepła oraz zwiększa średni współczynnik wnikania ciepła skracając czas potrzebny do osiągnięcia wymaganej temperatury. Przeprowadzone badania eksperymentalne wykazały wzrost liczby Nu od czoła napływu w kącie 0° oraz w tylnej części w kącie 180°, natomiast niewielki spadek w punkcie oderwania warstwy przyściennej w kącie 90÷110°. Wyniki badań uzyskanych podczas zaburzonego przepływu odniesiono do wyników uzyskanych podczas stabilnego przepływu spalin w komorze. W celu zapoznania się z zachowaniem warstwy przyściennej oraz rozkładem linii prądu przepływających spalin przeprowadzono symulacje numeryczne z wykorzystaniem programu FLUENT. Symulacje pozwoliły na zaobserwowanie zjawiska narastania warstwy przyściennej poczynając od czoła napływu znajdującego się w kącie 0° do punktu w którym następuje jej oderwanie. Tłumaczy to dlaczego następuje wzrost liczby Nu w tylnej części walca. Badania eksperymentalne były skomplikowane i wymagały opracowania indywidualnej metodyki i odpowiedniego oprzyrządowania do pomiarów w otoczeniu gorącego płynu. Różnorodność technik pomiarowych stosowanych przy chłodzeniu grzanego walca nie mogła być wykorzystana w eksperymencie gdzie walec nagrzewano strumieniem gorących spalin, ponieważ wysoka temperatura wykluczała możliwość ich zastosowania. Prowadzone są dalsze prace nad rozszerzeniem zakresu omawianych wyników badań co pozwoli na szersze rozpoznanie się z przedstawionym zjawiskiem.

1. Introduction

The interest in convective heat exchange can be assumed to have its beginnings in the year 1790. At that particular time, a note by Joseph Black appeared in the "*The General Effects of Heat*" review, which expressed interest in heat exchange caused by the motion of fluid. Nearly a hundred years had passed since the time of publication of that note before the first publications came out, which started to describe the physical phenomena occurring during the flow of a stream of fluid in the vicinity of a solid body. Later on, it was noted that the existence of a laminar boundary layer played a key role in heat exchange. The character of the occurring flow phenomena indicates that the value of the convective heat-transfer coefficient depends mainly on the thickness of a laminar film (the Prandtl film) that provides the highest resistance to heat conduction. The thickness of this film may vary, depending on numerous variables, including: surface and fluid temperatures, velocity, fluid density and viscosity, as well as the thermal conductivity, surface roughness and shape. The mathematical description of the laminar boundary layer was undertaken by Ludwig Prandtl in 1904. Shortly after Prandtl's discovery of the laminar boundary layer, Ernst Kraft Wilhelm Nusselt found the existence of a thermal boundary layer, different from the laminar boundary layer forming during fluid flow [1,2]. The thermal boundary layer forms in the case of a temperature difference occurring between the solid surface and the fluid. These two breakthrough discoveries initiated the development of a new chapter in the field of heat exchange. A number of studies concerned primarily natural convection [3,4,5], and then investigations were started, which were aimed at understanding the phenomena occurring during the forced flow of fluid around solid bodies [6,7,8]. The investigations were conducted in many aspects, considering different forms of flow-around, and a great diversity of research methodologies were applied. However, this did not bring about any significant results regarding the improvement in heat exchange conditions, therefore an attempt was made to use the forced introduction of oscillations into the gas flow [9,10,11].

When starting to conduct work on convective heat exchange during flow-around with a pulsatorily disturbed fluid stream, a conspicuous absence of publications was noted, which would present results of any studies on the flow around a cold cylinder by a hot fluid stream disturbed by pulsations.

2. The experimental stand

The experimental stand consists of three main elements of equipment. The first element, which is intended to maintain the appropriate thermal and flow conditions, is a ceramic heating chamber (Fig. 1). The heating up of the chamber is accomplished by means of combustion of a mixture of natural gas with air in a centrally positioned burner. Off-gas forming in combustion flows through the heating chamber into the flue, from which it is discharged outside [12,13]. The volume flux of flue gas flowing within the chamber is regulated by the appropriate feeding of gas and combustion air to the burner.

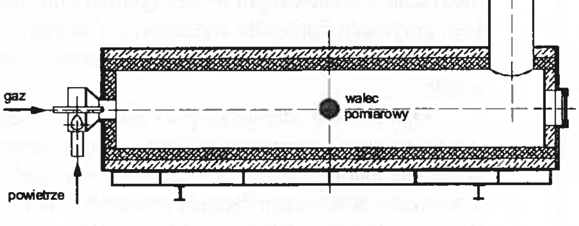

Fig. 1. The scheme of heating chamber

The second element of experimental stand equipment is a measurement cylinder positioned in the lateral axis of the heating chamber, flushed with flowing flue gas. The measurement cylinder is the main device for the determination of the local and average convective heat-transfer coefficient. The cylinder is made of the 2H13 stainless steel containing 13% Cr. Eleven longitudinal channels are made on the outer cylinder surface (Fig. 2) enabling the installation of NiCr-NiAl thermocouples that are covered with special metallic material having the properties of metal, and in particular holding a thermal conductivity similar to that of the cylinder material.

The cylinder body was subjected to strength tests under high pressure, and was also exposed to high temperatures.

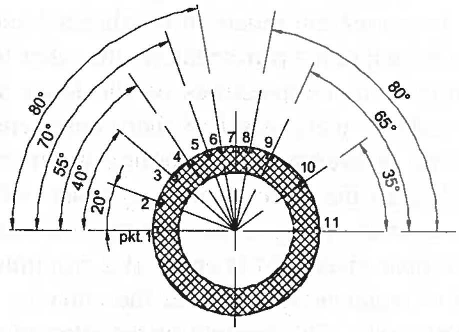

Fig. 2. The measurement points distribution

A set of tubes was inserted in the body interior to enable the cooling of the inner side of the cylinder with water of a strictly defined volume flux (Fig. 3).
The cooling system was made of copper tubes interconnected and partially thermally insulated. This prevents the cooling medium put into circulation from being excessively heated up by the medium discharged to the outside after being heated. The provision of a constant inner cylinder wall temperature at the point where the temperature measurement takes place assures the correctness of measurements being taken.

The set of tubes of the measurement cylinder inner wall cooling system provides a specific flow of the cooling medium, whose cold flux is delivered to a location situated in the centre of the measurement area passing through the longitudinal axis of the testing chamber. The flowing cooling medium forces the flow of heat to the cylinder centre, while the thermocouples situated in the measurement area measure the temperature at specific points.

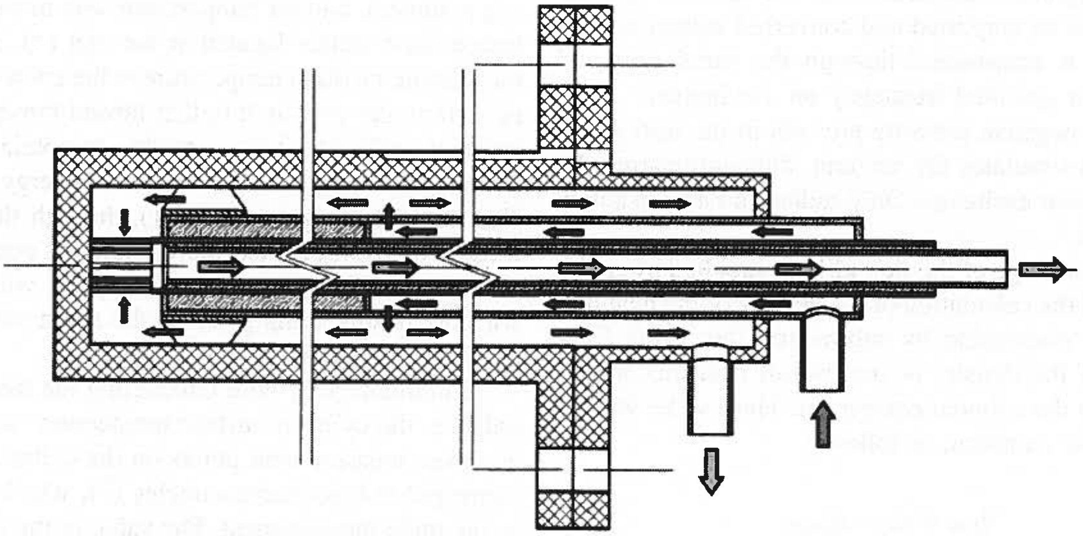

Fig. 3. The scheme of measurement cylinder with flow of cooling medium

The third element of the measuring equipment was an instrument for measuring the flux of heat supplied by thermal radiation. The experiment aimed at determining the convective heat flux, and thus the surface film conductance, is very difficult to carry out, in particular at an elevated temperature of the medium. In the case of cooling the cylinder with air at low temperature, the radiation of the walls and flue gas can be omitted.

The heating-up problems are much more difficult to examine due to the fact that the heat flux supplied to the surface is composed of the heat flux delivered with flue gas and wall radiation and the heat delivered by convection during the flushing of the cylinder with the hot flue gas flux. In order to determine the amount of energy supplied to the measurement cylinder solely by convection, the amount of energy supplied by radiation needed to be established. For this purpose, an instrument shown in Fig. 4 was used. This instrument makes it possible to measure the heat flux delivered solely by radiation and absorbed by a small area of the instrument head.

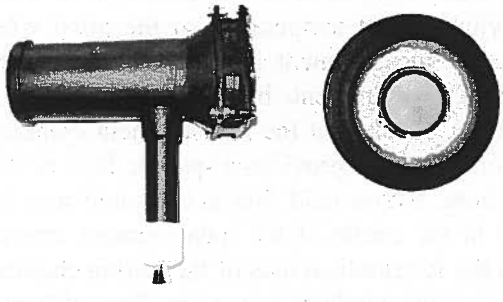

Fig. 4. The instrument to measure the heat flux by radiation

The head of the radiation measuring instrument is made of the material identical to that of the cylinder, therefore it is not necessary to know the emissivity of either the sensor head surface or the cylinder surface. The instrument head has strictly defined dimensions. It is mounted in a casing protecting against the contact with the body material, and, from the front side, it is covered with an eyepiece made of glass resistant to sudden changes in temperature. Additionally, an electronic system is provided, which processes thermal electromotive force impulses delivered from the sensor's sensing elements into an amplified and converted voltage signal. This signal is transmitted through the serial port and recorded at a specified frequency on a computer.

A deep negative pressure prevails in the instrument body, which simulates the vacuum, thus eliminating the convection heat exchange. Only radiation participates in heat transfer.

The knowledge of the flux of heat supplied by radiation enabled the calculation of the density of the heat flux supplied by convection by subtracting this value from the value of the density of the overall heat flux that is measured by the cylinder equipment. This can be written with a simple equation, as follows:

$$\dot{q}_{kon} = \dot{q}_{ca} - \dot{q}_{prom}$$

3. The experimental research

The heating chamber used in the experiment enabled the laboratory-scale simulation of conditions similar to those prevailing in industrial heating installations.

Before proceeding with measurements, the heating chamber was properly prepared by installing the measurement cylinder and measuring instruments, namely thermocouples, a radiation flux measuring instrument and an analyzer probe. Then, the gas burner was ignited. The amounts of air and gas supplied were controlled using rotameters. The temperature of flue gas flowing in before the cylinder was measured with an aspiration thermocouple.

The air flux was supplied from a fan through the pulsation generator system, where the pulsatory disturbing of the flow up to the frequency required in the experiment took place.

A schematic diagram of the measuring system for the determination of the convective heat-transfer coefficient on the cylinder surface (10) is shown in Fig. 5. The measurement methodology, as has already been mentioned, doubling measurements system was based. The checking measurement relied on the thermal energy balance. The principal measurement, on the other hand, was a measurement of temperatures on the inner and outer cylinder surfaces using a set of thermoelements (7). In the checking measurements, a cooling water stream (5) was supplied to the measurement cylinder, while measuring its quantity using a flow counter (2), and a temperature sensor installed (3) enabled a continuous measurement of water temperature at the entry to the measuring instrument. The cooling water allowed the inner side of the cylinder body to be cooled down and the temperature to be kept at a constant level. After flowing through the set of tubes, cooling medium left the measuring cylinders, and its temperature was measured by the temperature sensor located at the exit (4). By knowing the cooling medium temperature at the entry and the exit, as well as the volume flux that flowed through the measurement cylinder, it was possible to obtain the amount of supplied energy using the thermal energy counter (1). The thermal energy counter (1), through the integrated microprocessor, enabled the continuous computation of the amount of thermal energy supplied with the water, with the results being given as the mean value averaged for 3 minutes' time interval.

Simultaneously with conducting the thermal energy balance, the cylinder surface temperature was measured at eleven measurement points on the cylinder perimeter, using jacket-type thermocouples (7), which was treated as the main measurement. The value of the thermal electromotive force from the thermocouples was transmitted to the measuring card (8), thus providing the recording and archiving of the data on the computer at a frequency of approx. 200 Hz per channel (9). The measurement of the inner cylinder surface was taken using two jacket-type NiCr-NiAl thermocouples. Additionally, an aspiration thermocouple was placed in the heating chamber, which was intended for measuring flue gas temperature.

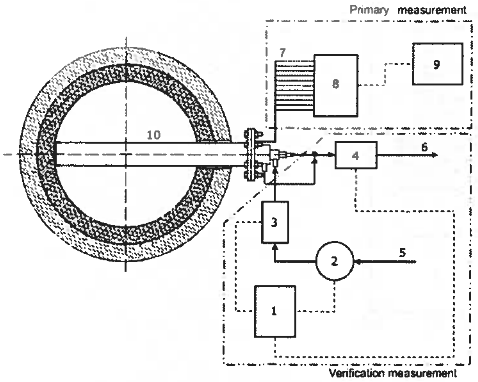

Fig. 5. The scheme of measurement and connective system

The principal aim of the experimental tests was to determine the effect of the frequency of pulsatory disturbance introduced on the value of the surface film conductance. In addition, tests were carried out to determine the effect of other parameters on the convective heat exchange, e.g. flue gas flow velocity, which is associated with the value of the Re number and the flue gas temperature in the vicinity of the measurement cylinder [14,15,16].

The determination of the effect of pulsation frequency in the range of 14÷74 Hz on the change of the local Nu number was conducted at three different average flue gas velocities in the chamber, amounting to, successively: 0.5 m/s, 0.6 m/s and 0.7 m/s for the flue gas temperature range of 250÷750°C.

The distribution of the Nu number as a function of the flue gas inlet angle and velocity is illustrated in Fig. 6. The results worked out indicate that the value of the Nu number strongly depends on the velocity of flowing flue gas. The increase in flue gas velocity from 0.5 to 0.7 m/s at some points on the cylinder perimeter caused an increase in the Nu number value by as much as 50%. An increase in the Nu number was also observed after the introduction of pulsatory disturbance to the flue gas at a specific frequency.

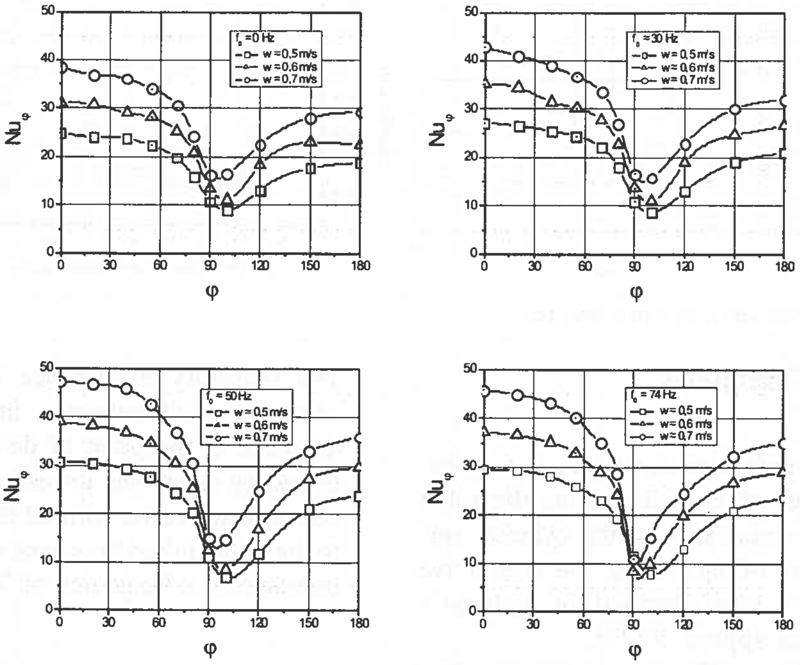

Fig. 6. The distribution of the Nu number as a function of the combustion gas inlet angle φ and velocity w. Combustion gas temperature 550°C

Heat exchange by convection is also dependent on the parameters of gas flowing and flushing an object under examination. The tests carried out have shown that the value of the local Nu number is dependent on the flushing flue gas temperature, decreasing with its increase (Fig. 7).

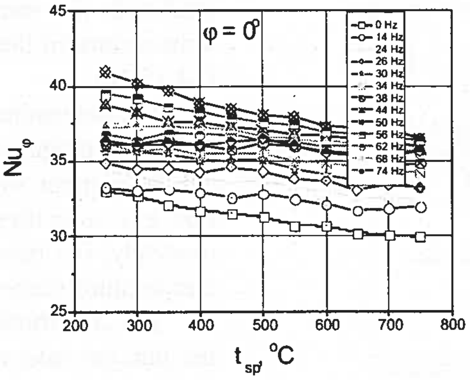

Fig. 7. The distribution of the Nu number as a function of the combustion gas temperature. Combustion gas velocity 0,6 m/s

The increase in flue gas temperature in the real conditions, under which the tests were carried out, resulted in a more rapid heating-up of the cylinder surface, but this was not solely due to convection, but also owing to the increasing share of heat radiation. To this end, correcting computations were carried out, which were aimed at isolating the heat flux delivered by convection from the overall heat flux supplied to the cylinder surface. The computations were made based on the knowledge the overall heat flux delivered to the cylinder. From these data, the percentage share of radiation in the overall heat flux was computed, which was reduced in the computation by the value of the local surface film conductance. The value of the overall heat flux with the isolated heat flux delivered by radiation is shown in Fig. 8.

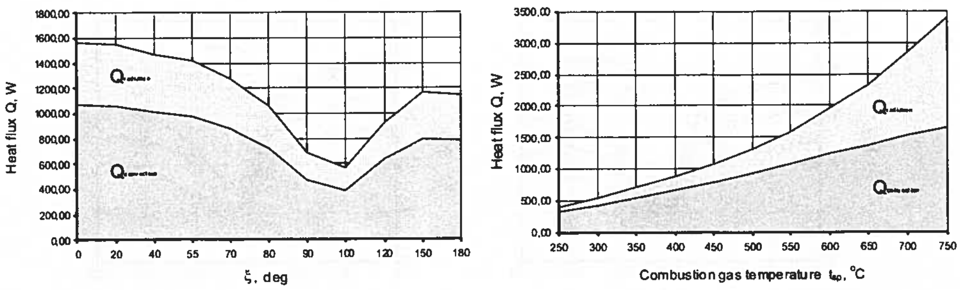

Fig. 8. The dependence radiation and convection heat flux

4. Conclusions

- The introduction of pulsatory disturbance at a specific frequency has an effect of increasing the value of the surface film conductance of the cylinder surface. The best results of increasing the convective heat exchange by 27% were obtained by applying a pulsation frequency of approx. 50 Hz.
- The temperature of flue gas flowing around the cylinder has an influence on the value of the average Nu number. The increase in the temperature results in a reduction of the Nu number value.
- The velocity of flowing flue gas in a specific temperature range has an influence on heat exchange by convection. Increasing the value of the Re number results in an increase in the local and average Nu number.
- The pulsatory disturbance introduced to the flow caused a local reduction in the surface film conductance at the point of detachment of the laminar boundary layer. The lowest value of the surface film conductance at the point of detachment, as compared to the undisturbed flow, was noted for introduced disturbance of a frequency of 74 Hz.

REFERENCES

[1] J. H. Lienhard IV, J. H. Lienhard V, A heat transfer textbook. Phlogiston Press. Cambridge-Massachustetts, USA 2001.

[2] F. L. Addessio, J. R. Baumgardner, J. K. Dukowicz, N. L. Johnson, B. A. Kashiwa, R. M. Rauenzahn, C. Zemach, CAVEAT: A

computer code for fluid dynamics problems with large distortion and internal slip. Los Alamos – National Laboratory, Mexico 1990.

[3] K. Kitamura, F. Kami-iwa, T. Misumi, Heat transfer and fluid flow of natural convection around large horizontal cylinders. International Journal of Heat and Mass Transfer **42**, 4093-4106 (1999).

[4] K. Kitamura, F. Kimura, Heat transfer and fluid flow of natural convection adjacent to upward-facing horizontal plates. International Journal of Heat and Mass Transfer **38**, 3149-3159 (1995).

[5] H. Koizumi, I. Hosokawa, Chaotic behavior and heat transfer performance of the natural convection around a hot horizontal cylinder affected by a flat ceiling. International Journal of Heat and Mass Transfer **39**, 1081-1091 (1996).

[6] S. Sanitjai, R. J. Goldstein, Forced convection heat transfer from a circular cylinder in crossflow to air and liquids. International Journal of Heat and Mass Transfer **47**, 4795-4805 USA (2004).

[7] S. Sanitjai, R. J. Goldstein, Heat transfer from a circular cylinder to mixtures of water and ethylene glycol. International Journal of Heat and Mass Transfer **47**, 4785-4794, USA (2004).

[8] M. Wen, K. Jang, Forced convection heat transfer at an inclined and yawed round tube. International Journal of Heat and Mass Transfer **45**, 2031-2042, Tajwan (2002).

[9] Fu W.S., Tong B.H.: Numerical investigation of heat transfer characteristics of the heated blocks in the channel with a transversely oscillating cylinder. International Journal of Heat and Mass Transfer **47**, 341-351 (2004).

[10] S. Krishnamoorthy, S. J. Price, M. P. Paidoussis, Cross-flow past an oscillating circular cylinder: synchronization phenomena in the near wake. Journal of Fluid and Structures 15, . 955-980 (2001).

[11] J. Carberry, J. Sheridan, D. Rockwell, Forces and wake modes of an oscillating cylinder. Journal of Fluids and Structures 15, 523-532 (2001).

[12] L. Szecówka, M. Górska, T. Janda, Analiza wpływu tarcia powierzchniowego na konwekcyjną wymianę ciepła podczas opływu strumieniem gazu okrągłego wsadu stalowego. Produkcja i Zarządzanie w Hutnictwie. XIII Konferencja Naukowo-Techniczna, 119-122, Częstochowa 2005.

[13] L. Szecówka, M. Górska, Konwekcyjna wymiana ciepła podczas opływu okrągłego wsadu stalowego zaburzonego pulsacyjnie strumieniem gazu. VI Międzynarodowa Konferencja Naukowa. Nowe technologie i osiągnięcia w metalurgii i inżynierii materiałowej, 76-79, cz.1. Częstochowa 2005.

[14] L. Szecówka, M. Górska, The Numerical Modelling of Pulsation Disturbance Flow Around a Circular Steel Charge. Acta Metall. Slovaca R.11 nr 1, 321-325, Slovak Republic 2005.

[15] M. Górska, L. Szecówka, T. Janda, Modelowanie numeryczne wprowadzanych zaburzeń w przepływie spalin w piecu przepychowym w celu zwiększenia wydajności. XIV International Scientific Conference, Iron and Steelmaking, Mala Lucivna 2004.

[16] L. Szecówka, Wpływ pulsacji na spalanie paliw gazowych i emisję zanieczyszczeń. Seria: Metalurgia nr 17, Częstochowa 2001.

Received: 20 June 2008.