

## Method of estimation of heat transfer coefficient between the fluidized bed and the surface immersed in it on an experimental simulation stand of a ship boiler

## Metoda określania współczynnika przejmowania ciepła pomiędzy warstwą fluidalną a powierzchnią w niej zanurzoną na eksperymentalnym stoisku symulacyjnym kotła okrętowego

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**Key words:** heat transfer coefficient, fluidized bed, experiment, ship boiler

### Abstract

The paper defines the meaning of local and average heat transfer coefficient. The most frequently applied experimental methods for its estimation, particularly between the fluidized bed and the surface immersed in it, are presented. The method for the estimation of the influence of position and movement of fluidizing column on heat transfer coefficient is proposed.

**Słowa kluczowe:** współczynnik przejmowania ciepła, warstwa fluidalna, eksperyment, kocioł okrętowy

### Abstrakt

W artykule zdefiniowano pojęcie lokalnego i średniego współczynnika przejmowania ciepła. Przedstawiono najczęściej stosowane eksperymentalne metody jego wyznaczania, w szczególności między warstwą fluidalną i zanurzoną w niej powierzchnią, również na tle własnej metody. Zaproponowano sposób określenia wpływu położenia kolumny fluidyzacyjnej, jak i jej ruchu na wartości współczynników przejmowania ciepła.

## Introduction

The determination of the value of heat transfer coefficient in the fluidized bed of a ship boiler using an experimental method on the industrial scale would require significant financial resources. The complexity of this task is additionally greater in the conditions of ship movement simulation, even if it is only restricted to the rolling motion to simplify the problem.

Literature referring to heat exchange in such conditions is therefore scarce and its review is

given, among others, in [1, 2]. However, there is no evidence of studies on the influence of swaying of the fluidizing column on the process of heat transfer in the fluidized bed. To estimate the influence of such disturbance on heat exchange, it is convenient to present the changes of the heat transfer coefficients in different parts of the fluidizing column. It particularly refers to the circulating fluidized bed. Our own observations [1], as well as descriptions of hydrodynamics of the circulating fluidized bed [3] allow us to state that

the structure of the fluidized bed is characterized by the following:

- distribution of grains of the loose material within the whole volume of the column,
- decreasing concentration of the loose material along the height of the column, with the tendency to its more equal distribution with an increase of gas flow,
- relationship between local concentrations and speed of gas flow and the amount of loose material in the system,
- non-homogenous distribution of loose material concentrations in the cross-section of the column with a significant minimum at the axis and maximum at its sides.

An analysis of spatial temperature contribution in the bed presented among others in [4, 5] can be an alternative to studies on the heat transfer coefficient in relation to heat exchange in the fluidised bed.

Descriptions of methods and ways of measurement of heat transfer coefficients between the fluidized bed and a surface immersed in it, performed on physical models corresponding with the conditions of a boiler operating on land, can be found in numerous studies [3, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The aspect described here, based on our own method [1, 2] they will be discussed in the further part of this paper.

Concepts of local and mean heat transfer coefficients have been defined as they are indispensable for the needs of this study for proper interpretation and evaluation of the experimentally obtained heat transfer coefficient estimations. Thus, clues for uniform terminology in the field of heat transfer in a fluidized bed have been established.

### Local and mean heat transfer coefficient

The heat exchange between the surface of a solid and a fluid washing it is called heat transfer, and mathematically it is described by Newton's equation in one of the two forms:

$$\dot{Q} = \alpha A (T_w - T_f) \quad (1)$$

or:

$$q = \alpha (T_w - T_f) \quad (2)$$

where:  $\dot{Q}$  – flux of the transferred heat,  $q$  – density of heat flux,  $T_w$  – temperature of the solid surface,  $T_f$  – temperature of the fluid at a large distance from the surface of the solid (the temperature of the fluid outside the thermal layer adherent to the wall is taken here),  $A$  – the surface,  $\alpha$  – heat transfer coefficient.

The heat transfer coefficient  $\alpha$ , which from the mathematical point of view is a proportionality constant in Newton's equation, physically is the measurement of heat transfer intensity in the process of heat exchange. It depends on thermo-physical properties of the fluid, kinematics of the fluid flux, the shape of the heat transfer surface taking part in the process, kind of convection taking place (natural, forced) and the possible accompanying phase changes.

The value of the heat transfer coefficient can change in time and in all directions on the whole washed surface. At the same time the temperatures of the fluid and of the surface can change. For this reason a local heat transfer coefficient,  $\alpha_{lok}$  defined as:

$$\alpha_{lok} = \frac{d\dot{Q}}{dA} \frac{1}{T_w - T_f} \quad (3)$$

as well as the mean coefficient are considered. Relation (3) states that the local heat transfer coefficient refers to a very small surface  $dA$  which surrounds the examined point [12].

The mean value of the heat transfer coefficient can be calculated from integrating the values of local heat transfer coefficients over surface  $A$  according to the following equation:

$$\alpha_{sr} = \frac{\int_A \alpha_{lok} (T_w - T_f) dA}{\int_A (T_w - T_f) dA} = \frac{\dot{q}}{(T_w - T_f)_{sr}} \quad (4)$$

Methods of averaging of the heat transfer coefficient (as well as of the temperatures) are conventional and can be different [13]. First of all, they depend on the kind of heat transfer surface and the way in which it is washed by the fluid.

In some problems the need to average the local coefficient in time may arise. In this situation the mean value of the local heat transfer coefficient in time is defined as follows [17]:

$$\alpha_{lok_{sr}} = \frac{1}{n} \sum_{i=1}^n \frac{\dot{q}_{lok_i}}{T_{w_i} - T_{f_i}} \quad (5)$$

where:  $n$  – the number of measurements in an examination in a defined period of time.

In the case of a significant non-homogeneity of the fluid i.e. the fluidized bed, placing the heating surface in different places within the whole column space may give different values of both local and mean heat transfer coefficients. In both cases there will be a spatial distribution of their values in the volume of the column, which will be a function of surface location. Thus, a determined location of the

surface does not mean a ‘local character’ in the sense of the definition of a local heat transfer coefficient, but it has a more general meaning and its change also affects the mean value of the heat transfer coefficient.

## Methods of determination of heat transfer coefficient

The values of heat transfer coefficient are determined experimentally by an indirect method or by direct ones [14].

In the indirect method we have to know the temperature field in the fluid adherent to the wall, in which heat exchange takes place. On this basis, using Fourier’s law describing in this case heat transfer in the laminar layer of the fluid at the wall, local values of heat transfer coefficients are determined. Comparing Fourier’s equation in the form:

$$\dot{q} = -\lambda \frac{\partial T}{\partial n} \quad (6)$$

where:  $\lambda$  – thermal conductivity coefficient of the fluid,  $\partial T / \partial n$  – gradient of the fluid temperature, to equation (2) the local heat transfer coefficient is determined from the following relation:

$$\alpha_{lok} = \frac{-\lambda \left( \frac{\partial T}{\partial n} \right)_w}{T_w - T_f} \quad (7)$$

where:  $(\partial T / \partial n)_w$  – gradient of the fluid temperature in the coordinate perpendicular to the wall.

This relation requires the knowledge of the thermal conductivity coefficient of the fluid, and in the case of a fluidized bed its determination turns out to be a complex task. This method is also called a theoretical method as the temperature field is determined from differential equations of continuity, movement and energy.

Direct methods of determination of heat transfer coefficient most often applied for technical purposes use Newton’s law. From equation (1) or (2) the heat flux or its density are determined for a known surface of heat transfer and experimentally determined temperatures of the wall and fluid. In this way most often the mean value of the heat transfer coefficient is determined with the highest reliability, as the total value of the flux of heat supplied to the fluid from the whole wall surface (or in the reverse direction).

These methods can be divided into three categories: stationary (static), transient (dynamic) and analogue ones [15].

In the static method, otherwise known as the method of stable heat flux, the approach to heat flux measurement depends on the kind of heat source used. Due to the simplicity of measurement and the condition of maintaining constant density of heat flux ( $q = \text{idem}$ ) on the wall surface, it is particularly convenient to apply electrical heating. Very often the wall is at the same time an electrical resistor which emits heat or it is an outer insulation of the heating element (inner heater). The value of the heat flux is determined from the power of current by measuring current intensity and voltage drop on the resistor or other heating element or resistance

$$\dot{Q} = UI = I^2 R \quad (8)$$

where:  $U$  – voltage drop on the resistor or heating element,  $I$  – intensity of electrical current,  $R$  – electrical resistance of the heating resistor.

Another popular solution is to use a heating element in the form of e.g. a tube, where saturated steam or water is the source of heat. Heating the wall with condensing steam at a constant pressure allows to treat it as an isothermal surface. It creates univocal conditions for the determination of local values of the heat transfer coefficient. In both cases the heat flux is determined from the heat balance equation, where the mass flux of the heating medium  $\dot{m}$  and its enthalpy at the intake  $i_{wl}$  and at the outlet  $i_{wyl}$  of the heating element are known:

$$\dot{Q} = \dot{m} (i_{wl} - i_{wyl}) \quad (9)$$

Wilson’s method, based on the heat balance of the heat exchanger is used to determine the mean heat transfer coefficient at the surfaces of recuperators. It is not useful in the analyzed case and is not discussed here.

In the transient (dynamic) method, the use of exponential heating state or cooling of an object of a low heat resistance dominates (Biot’s number  $Bi < 0.1$ ). The determination of heat transfer coefficient requires the construction of a model of the studied object (to obtain the mean coefficient), or its part (to obtain local heat transfer coefficients). The model and its part (alphacalorimeter) are so constructed that the heat losses would be limited, using materials of low heat resistance. Assuming an equalized temperature distribution in the cross-section of the model, which is permitted in the case of spheres and cylinders for example, the heat transfer coefficient is determined from the following heat balance equation:

$$\alpha_{sr} = \frac{m_s c_s}{A_s (T_s - T_f)} \frac{dT_s}{dt} \quad (10)$$

where:  $m$  – mass of the model,  $c_s$  – specific heat capacity of the material from which the model is made,  $A_s$  – surface of the model,  $T_s$  – surface temperature.

Analogue experimental methods of heat transfer coefficient determination are based on similar physical phenomena, i.e. those that can be described by the same mathematical relations. Physical quantities playing the same mathematical roles are called analogues. Such analogies exist between the phenomena of heat transfer and the transfer of momentum. Electrical analogies are also often used, where the analogue of the temperature is either the voltage or the current [18].

Analogue methods turned out to be inadequate for the character of the studied phenomenon and are not a subject of further discussion herein.

### Methods of investigations of heat transfer coefficient in the fluidized bed

The value of the coefficient of heat transfer between the fluidized bed and the object surface object is treated (after some simplifications) as a sum of three components [13]:

$$\alpha_{sr} = \alpha_c + \alpha_p + \alpha_r \quad (11)$$

where:  $\alpha_c$  – corresponds to the transport of heat by elevated particles between the area directly adherent to the surface and the fluidized bed (convection of particles of the material of the fluidized bed),  $\alpha_p$  – it represents the participation of air convection in the process of heat transport between the surface and the fluidized bed,  $\alpha_r$  – it corresponds to heat exchange via radiation.

Studies on heat transfer coefficients are often carried out at moderate temperatures of the heating element (usually up to 200°C), then as non-significant the following are neglected: the heat flux to the environment, the conducted heat flux and the heat flux transferred through radiation [19].

For the precise determination of the derivative  $dT_s/dt$  in equation (10) it is necessary to have equipment with high sampling speed, thus the dynamic method is used only sporadically. In paper [10] it was experimentally shown that results obtained by the static and dynamic method are comparable, which favours the use of a simpler and cheaper static method for estimating the value of heat transfer coefficient.

In the static methods applied for studies on heat transfer coefficient between a fluidized bed and the

surface immersed in it, most often spherical or cylindrical heated probes are employed. In paper [3] a brass spherical probe of 0.019 m diameter, inside which there was a heating element, was used. The temperature of the probe wall was measured with one thermocouple located on its surface. To limit heat losses, the sphere is separated from the handle by insulating material in the form of a teflon sleeve. The temperature of the bed was measured with a thermocouple located at a certain distance from the probe wall. The heat transfer coefficient was measured at the cross-sections of the column at several levels along its height. The measurement probe in each cross-section was placed at several points along the column radius. The value of the heat transfer coefficient was determined from relation (1). Description of the studies shows that the authors assumed that the probe wall was isothermal, and the determination of the values of heat transfer coefficients is local in character. In fact, the measurement was carried out in the same way as that for the determination of the mean value of the coefficient, which simplified the process.

In paper [9] for measuring the mean heat transfer coefficient, a tube with the diameter of 0.0096 m and the length of 0.6 m to which hot water was supplied was used as a heating element. Heat flux was calculated from (9) and the mean heat transfer coefficient from the transformed equation (1). The wall temperature was measured in two places and the value was averaged. The tube was located in the axis of the column in a vertical position. The temperature of the fluidized bed was measured in three places along the tube; at the top, in the middle and at the bottom, and then the values were averaged. The tube was placed at different heights of the column. A diagram showing the stand is presented in figure 1.

The results of studies of the values of the mean heat transfer coefficients versus the height of the fluidized bed were shown in paper [20]. In this study the heating element was a tube 0.3 m long and 0.025 m in diameter, with an electric heater inside. The temperatures of the tube and the bed were measured with thermocouples and after averaging them. The mean heat transfer coefficient was calculated from the transformed equation (1), with the heat flux previously determined from equation (9).

In many cases studies on heat absorption coefficients are performed with the use of devices for measuring flux density. Electrically heated detectors, the so called active ones, are most often used for this purpose [16]. The heat flux is then calculated from equation (8). After dividing its value by

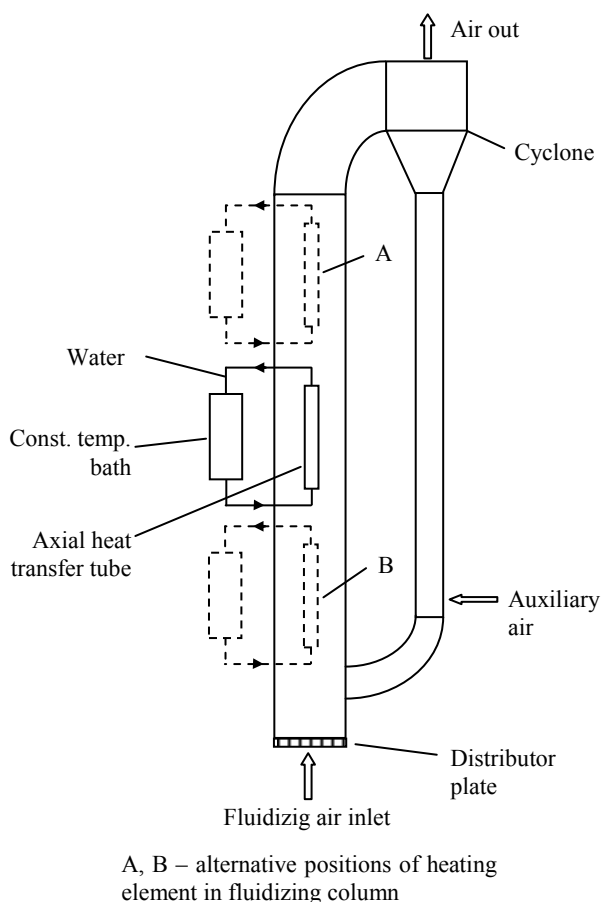


Fig. 1. Diagram of a stand with water heater for the determination of heat transfer coefficients

Rys. 1. Schemat stanowiska z podgrzewaczem wody do określania współczynników przenikania ciepła

the known surface of the detector, density of the heat flux is obtained. As electrical resistance is a function of temperature, it can be used for measuring the temperature on the detector surface. Now only the temperature of the bed remains to be measured with a thermo-element. Constructions of detectors are different and they can be extensively miniaturized. In such constructions, a resistance detector is simultaneously a source of heat and a heat density meter. A certain drawback of such detectors is partial loss of heat to the base through-out the insulation.

Other concepts of meters for determining heat transfer coefficients are also applied. Here, a resistance heater is used to create the heat flux and the heat flux density is measured by a detector of the "auxiliary wall" type [16]. Figure 2 shows a diagram of such a meter, where thin micro-foil is the flux detector. To determine the coefficient of heat transfer to the bed, apart from the meter, also a thermo-element is needed for measuring the temperature of the fluidized bed.

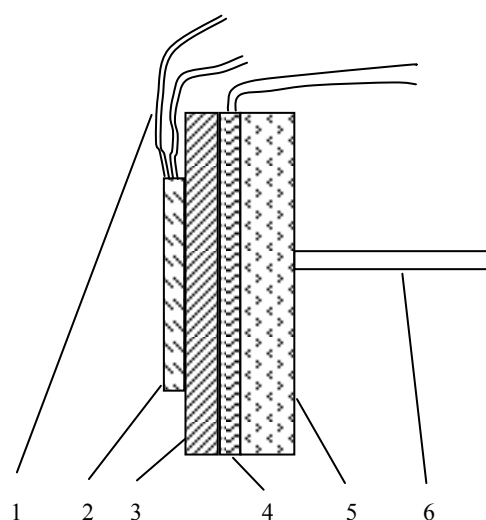


Fig. 2. A diagram of a meter for the determination of heat transfer coefficient [16]: 1 – electrical leads, 2 – micro-foil heat flux sensor, 3 – copper plate, 4 – heater, 5 – heat insulation, 6 – handle

Rys. 2. Schemat licznika do określania współczynnika przenikania ciepła [16]: 1 – przewody elektryczne, 2 – czujnik strumienia ciepła, 3 – miedzioryt, 4 – grzałka, 5 – izolacja cieplna, 6 – uchwyt

The sensors for measuring heat flux of the type described above were used for studying averaged in time local heat transfer coefficients in the fluidized bed described in paper [11]. The diagram of the probe which was used there is shown in figure 3.

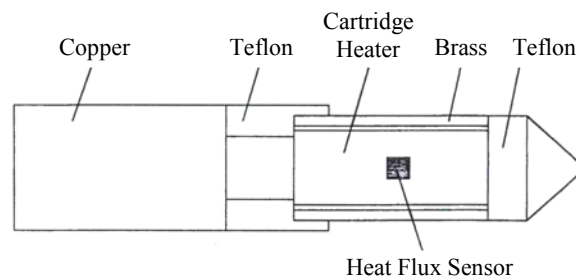


Fig. 3. Diagram of a probe with a heat flux sensor [11]

Rys. 3. Schemat sondy z czujnikiem strumienia ciepła [11]

### Test stand and the applied methodology of simulation studies on the marine fluidized bed boiler

The stand for research was constructed with the assumption that it should enable carrying out researching processes taking place in boilers with a bubbling fluidized bed and also in boilers with a circulating fluidized bed in conditions simulating ship's movement on sea waves. To meet this demand, the fluidized column of a boiler model was placed on a float which can lean in one plane to the left or to the right from the vertical direction by 30° simulating ship's rolling on regular waves of sinusoidal character. It has also been assumed that

the ship is on even keel. The diagram of the research stand of a fluidized bed boiler is presented in figure 4.

The basic structural element is the fluidizing column (Fig. 4 – 1) in the shape of a tube 2 m long with the inner diameter  $D_w = 0.094$  m, made of plexiglass. A relatively moderate column diameter makes it possible to obtain air flow speeds in the circulating fluidized bed up to 13.5 m/s. Fluidizing air is supplied by a blower (2), powered by an electric motor. Thanks to the fact that the engine is located outside the casing of the blower, the air does not get heated by it. Otherwise the heated air could pronouncedly disturb the experimental results of studies on heat transfer in the bed. The volume of the air flux supplied by the blower can be regulated in the range from 0 to 0.1083 m/s throughout continuous change of the rotational speed of the motor.

The swaying movement of the float together with the column, blower and measuring equipment is carried out by an actuator (7) with a regulated speed of the plain motion and thus the frequency of swaying can be changed.

Studies on the heat transfer coefficient are carried out using a method similar to that which was described in paper [3], the difference, however is that instead of a spherical probe, a miniature cylindrical one has been used. The source of heat necessary for the determination of the averaged in time local heat absorption coefficients is a heating element – electrical heating coil placed in a copper tube (15) of 0.05 m length and the diameter of 0.015 m submerged in a fluidized bed. The inside of the tube is filled with sand, increasing its heat inertia and uniformity of wall heating. Teflon rods were placed in both ends of the tube in order to limit heat losses from the front walls. Thanks to such

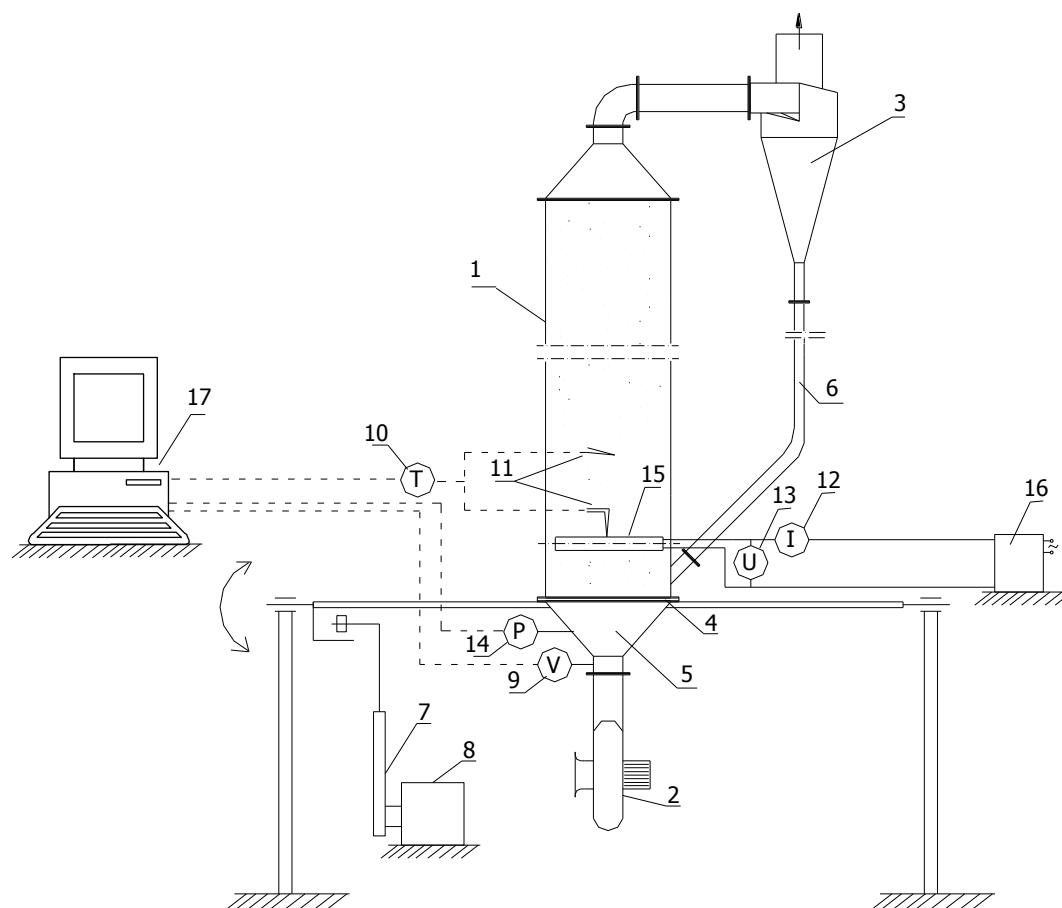


Fig. 4. Diagram of a laboratory test stand of the fluidized bed boiler: 1 – fluidizing column, 2 – blower, 3 – cyclone filter deduster, 4 – separating grid, 5 – air box, 6 – down pipe, 7 – actuator, 8 – electric motor, 9 – thermometer-anemometer, 10 – temperature recorder, 11 – thermocouples, 12 – ammeter, 13 – voltmeter, 14 – differential pressure gauge, 15 – heating element, 16 – electrical power pack, 17 – computer

Rys. 4. Schemat stanowiska badawczego kotła fluidalnego: 1 – kolumna fluidyzująca, 2 – dmuchawa, 3 – cyklon osadnika filtra, 4 – oddzielenie sieci, 5 – pole powietrza, 6 – dolna rura, 7 – siłownik, 8 – silnik elektryczny, 9 – termometr-wiatromierz, 10 – rejestrator temperatury, 11 – termopary, 12 – amperomierz, 13 – woltomierz, 14 – manometr różnicy, 15 – element grzewczy, 16 – zasilacz elektryczny, 17 – komputer

construction of the heating element it was possible to assume isothermal character of the wall which, however, brings about certain inaccuracy. To evaluate the disturbance caused by column swaying on the process of heat transfer it was acknowledged that the inaccuracy was acceptable from the engineering point of view. The temperature of the heater wall is measured by a thermocouple fixed to its surface. Thermo-elements for the measurement of the fluidized bed temperature were located at three points in one line along the probe. Owing to this, it is possible to determine an approximate distribution, averaged in time, of the local heat absorption coefficient. The power of the heater can be continuously regulated in the range from 0 to 100 W and monitored with a digital ammeter (12) and a digital voltmeter (13).

It was assumed that the studies would be carried out at a low temperature of the fluidized bed in which the exhaust gas would be replaced by air. To measure the speed of air flow, a digital thermometer-anemometer (9) was used. The resistance of air flowing through the grid and the bed is measured with a digital differential pressure gauge (14). Both meters were equipped with software for real time data transmission to a computer (17), which enables storage of experimental results. The temperature of the tube surface and the fluidized bed is measured by a multi-channel digital temperature recorder (10) that can be connected to ten thermocouples (11) and which itself is connected to the computer. Thermocouples of the NiCr-NiAl type are used in the described stand.

The distribution of thermocouples and the location of the heater in the bed for carrying out studies on local heat absorption coefficients were chosen on the basis of observations of bed behaviour at different speeds of fluidizing air flow and different heights of the bed in the stationary state. Thermocouples were placed over the heater in two rows in the symmetry plane of the column and the heater. A diagram of distribution of the heater and thermocouples inside the column and the distances among them is presented in figure 5 [1].

Thermocouples in the upper row were of secondary importance and were used merely for checking the temperature from the first row. Their results guarantee that the temperature of the fluidized bed is taken outside the thermal layer adherent to the tube wall.

The construction chosen for this stand allows to place the heating element in one of two positions i.e. in the conventional plane of symmetry of the ship or in the plane perpendicular to it (in the frame plane). In both cases the heating element (tube)

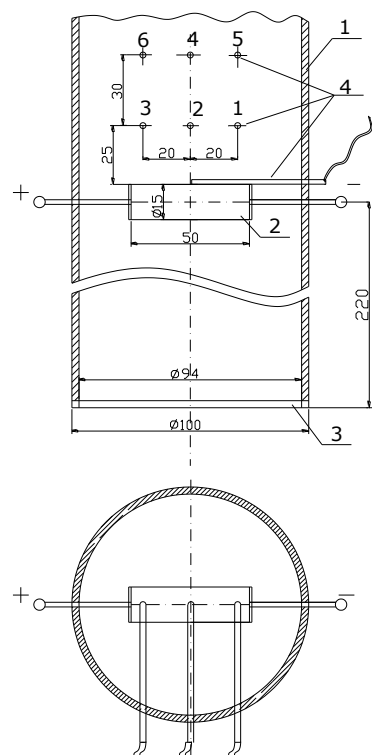


Fig. 5. Distribution of the heater and thermocouples in a fluidizing column: 1 – fluidising column, 2 – heating element, 3 – separating grid, 4 – thermocouples [1]

Rys. 5. Rozmieszczenie grzejnika i termopar w kolumnie fluidyzującej: 1 – kolumna fluidyzująca, 2 – element grzejny, 3 – oddzielenie sieci, 4 – termopary [1]

remains in the position which is perpendicular to the axis of the column.

## Summary

The heat transfer coefficient in the fluidized bed of a ship boiler can be determined first of all through an experimental method. Performing this task in real sea conditions would be almost impossible and would require substantial financial resources. Therefore, it is justified to use a physical model of a fluidized bed ship boiler. The complexity of the task will additionally increase with the introduction of ship movement on the waves, even if in the simulation it is only limited to rolling.

The measurement of heat transfer between the fluidized bed and the surface immersed in it is the local or mean heat transfer coefficient.

Most frequently, the simple direct and easily accessible static methods are used for estimating heat transfer coefficients. Less practical, only sporadically applied in specific cases, are indirect dynamic methods which use Fourier's law. Here, it is essential to know the temperature field in the volume of the fluid adherent to the wall, in which heat transfer takes place. It makes sophisticated demands on the control equipment for precise

determination of the speed of temperature changes. On the basis of these results local values of heat transfer coefficients are determined.

The comparability of results of heat transfer coefficients in the fluidized bed of different ship boilers can be ensured by choosing a method suitable for both the bubbling and the circulating fluidized bed. The presented method is based on a unique phenomenon of a fluidized bed ship boiler model with a bubbling or circulating bed, which enables simulation of operation similar to that which takes place in sea conditions. The possibility to test different beds is obtained thanks to a blower with a wide range of efficiency variation. In the scheduled study program using the presented method, it is planned to determine the tendency of changes in the distribution of the averaged in time local heat transfer coefficients at a stable ship listing or simulated rolling on a regular wave of sinusoidal character. Mean heat transfer coefficients as a function of the column swaying period will also be determined. The hypothesis that conditions for heat transfer in the circulating fluidized bed are more advantageous at column swaying than at the time when it is stationary will also be verified.

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