# MEASUREMENT OF HEAT TRANSFER COEFFICIENT

The aim of the exercise is to identify the heat transfer coefficient using the quasi-static method with a sample of known thermal conductivity.

## 1. THEORETICAL INTRODUCTION

The measurement of the heat transfer coefficient involves experimental studies of heat transfer, in which a stream of heated air strikes perpendicularly on the front surface of a cylindrical sample made of a material with known thermal conductivity. A directed stream of fluid or gas can effectively transfer large amounts of energy as heat between the surface and the surrounding fluid.

### 1.1 HEAT CONDUCTION

Heat conduction involves the transfer of internal energy between parts, contacting directly one or different bodies. Heat conduction occurs in liquids, solids, and gases. The primary mechanism of heat conduction in solids is through quantised vibrations of the crystal lattice and the ordered movement of free electrons (metals and metal alloys). In contrast, in liquids and gases, the heat conduction mechanism is related to the transfer of kinetic energy during collisions of medium molecules.

Heat conduction is described by Fourier's law:

*Fourier's law, where* the density of the conducted heat flux is directly proportional to the temperature gradient:

$$q = -\lambda \nabla T \tag{1}$$

In the Cartesian coordinate system:

$$q = -\lambda \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) \tag{2}$$

that is:

$$q_x = -\lambda \frac{\partial T}{\partial x}, \quad q_y = -\lambda \frac{\partial T}{\partial y}, \quad q_z = -\lambda \frac{\partial T}{\partial z} \tag{3}$$

in the one-dimensional case:

$$q = -\lambda \frac{\partial T}{\partial x} \tag{4}$$

The coefficient $\lambda$ appearing in formulas (1), (3), and (4) is the proportionality coefficient that characterises the medium ability of the tested to conduct heat under steady-state heat transfer conditions. This coefficient is called the thermal conductivity or is referred to as the heat conduction coefficient.

### 1.2 CONVECTION

Convection is a type of heat transfer between a solid body and the fluid that flows around it. It involves the transfer of internal energy due to the movement of macroscopic parts of the fluid at different temperatures, and therefore different densities.

When mass forces act on parts of the fluid at different temperatures, we are dealing with free convection. On the contrary, when fluid movement is caused by external factors, such as ventilation devices, pumps, compressors, or wind, we deal with forced convection. The amount of heat exchanged during this type of heat transfer depends on the temperature difference, as described by Newton's law:

$$q = \alpha \cdot A \cdot \left(T_s - T_f\right) \tag{5}$$

where:

- $\alpha$ - heat transfer coefficient,

- $T_s$ - wall temperature,

- $T_f$ - fluid temperature.

Rewrite Equation (5) as:

$$q = \frac{T_s - T_f}{\frac{1}{\alpha}} \tag{6}$$

and knowing the surface area $A$, we can determine the heat transfer resistance for a flat wall as:

$$R_\alpha = \frac{1}{\alpha \cdot A} \tag{7}$$

For a cylindrical wall, the heat transfer resistance is given by:

$$R_\alpha = \frac{1}{2\pi r L \alpha} \tag{8}$$

In the case of heat transfer between fluids separated by a solid wall, we refer to heat penetration. This phenomenon involves heat transfer at both surfaces of the wall and conduction through the solid wall.

The specific resistance of heat penetration through a flat, multilayer wall is described by the equation:

$$\mathrm{r_{kp}} = \frac{1}{\alpha_1} + \sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2} \tag{9}$$

and for a multilayer cylindrical wall:

$$r_{kp} = \frac{1}{2\pi\, r_1 \alpha_1} + \frac{1}{2\pi} \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{r_{i+1}}{r_i} + \frac{1}{2\pi\, r_2\, \alpha_2} \tag{10}$$

Introducing the heat penetration coefficient $k$, the density of the heat flux penetrating through the wall can be described using Peclet's law, which forms the basis for describing the phenomenon of heat penetration:

$$\mathrm{q} = \mathrm{k} \cdot \left(\mathrm{T}_{p1} - \mathrm{T}_{p2}\right) \tag{11}$$

where: $k$ – heat penetration coefficient, $T_{p1}$ – inlet fluid temperature, $T_{p1}$ – outlet fluid temperature.

The heat penetration coefficient for a flat multilayer wall is expressed by the formula:

$$k = \frac{1}{r_{kp}} = \left(\frac{1}{\alpha_1} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}\right)^{-1} \tag{12}$$

and for a multilayer cylindrical wall:

$$k = \frac{1}{r_{kp}} = \left( \frac{1}{2\pi r_1 \alpha_1} + \frac{1}{2\pi} \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{r_{i+1}}{r_i} + \frac{1}{2\pi r_2 \alpha_2} \right)^{-1} \tag{13}$$

### 1.3 THERMAL RADIATION

Thermal radiation involves the emission of electromagnetic waves by bodies with temperatures above absolute zero. It occurs between bodies separated by a medium that is transparent to thermal radiation or even through a vacuum. During heat transfer by radiation, the internal energy of a body is converted into electromagnetic radiation energy, which, upon encountering another body or part of the same body, is absorbed and transformed back into internal energy.

To describe electromagnetic waves, we use the concept of wavelength $\lambda$ or frequency $v$, along with the speed of light $c$. The relationship between these parameters is given by the following:

$$\lambda = \frac{c}{\nu} \tag{14}$$

Thermal radiation can occur at selected wavelengths ranging from 0 to ∞. In the context of heat transfer, the most significant wavelength range is 0.4–1000 µm, where:

1. 0.38–0.78 µm – visible light range,
2. 0.78–2.5 µm – near-infrared range,
3. 2.5–25 µm – mid-infrared range,
4. 25–1000 µm – far-infrared range.

Radiation can also be classified by its frequency:

1. Monochromatic radiation – involves a single frequency,
2. Panchromatic radiation – involves all frequencies,
3. Selective radiation – involves a specific band of frequencies.

When thermal radiation strikes the surface of a body, it is partially absorbed (a - absorption coefficient), reflected (r - reflection coefficient), and can also be partially transmitted (p - transmission coefficient). The sum of these coefficients equals:

$$a + r + p = 1 \tag{15}$$

The energy flux of self-emitted radiation in all directions is denoted by $E$ and is called the emission flux. The emission flux per unit area of the emitting surface is referred to as the emission flux density, expressed as:

$$e = \frac{dE}{dA} \tag{16}$$

The emission flux density of a perfect black body is described by Planck's law:

$$e_{\lambda c} = \frac{2\pi h c_0^2}{\lambda^5 \left[ \exp\left( \frac{h c_0}{k \lambda T} \right) - 1 \right]} = \frac{C_1}{\lambda^5 \left[ \exp\left( \frac{C_2}{\lambda T} \right) - 1 \right]} \tag{17}$$

where:

$h = 6{,}6256 \times 10^{-34}$ $[\mathrm{J} \cdot \mathrm{s}]$– Planck's constant,

$k = 1{,}3805 \times 10^{-23}\left[\frac{\mathrm{J}}{\mathrm{K}}\right]$ – Boltzmann's constant,

$C_1 = 2\pi h c_0^2 = 3{,}74 \times 10^{-16}\,[\mathrm{W} \cdot \mathrm{m}^2]$ – first Planck constant,

$C_2 = \frac{hc_0}{k} = 14388\,[\mu\mathrm{m} \cdot \mathrm{K}]$– second Planck constant.

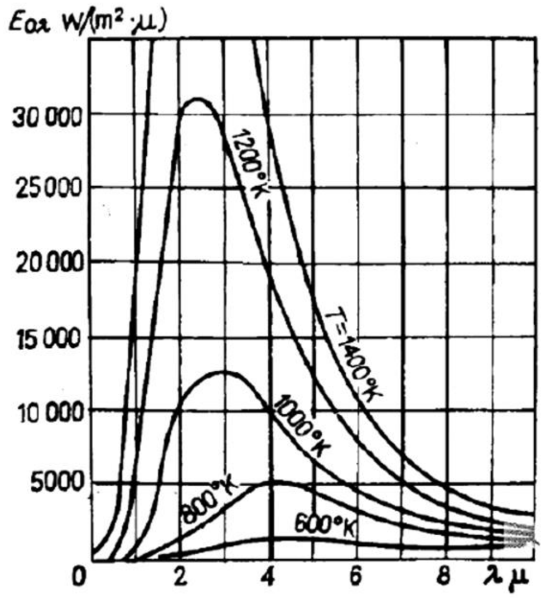


**Fig. 1.1**: Relationship of the monochromatic emission flux density of a perfect black body with wavelength and temperature.

The maximum density of monochromatic emission flux of a perfect black body (Fig. 1.1) is reached when the condition known as Wien's law is satisfied:

$$\lambda_m T = C_3 = 2897{,}6\,[\mu\mathrm{m} \cdot \mathrm{K}] \tag{18}$$

Substituting $\lambda_m$ into equation (17), the maximum is given by:

$$e_{\lambda m} = C_4 T^5 \tag{19}$$

where:

$C_4 = 1{,}286 \cdot 10^{-5}\left[\frac{\mathrm{W}}{\mathrm{m}^3\mathrm{K}^5}\right]$.

By integrating Planck's formula (17) over the entire wavelength range from 0 to ∞, we obtain the formula for the Stefan-Boltzmann law:

$$e = \sigma \cdot T^4 \tag{20}$$

where: $\sigma = 5{,}67 \cdot 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}}$ – Stefan-Boltzmann constant.

Equation (20) allows one to determine the density of the panchromatic emission flux of a perfect black body.

## 1.4 HEAT TRANSFER

Heat transfer is the exchange of heat between the surface of a solid body and the fluid that flows around it. Heat transfer by convection is described by Newton's law (5). The heat transfer coefficient becomes a key parameter when we want to estimate the heat flux density transferred from a fluid at a given temperature to the surface of a solid body at a different temperature.

Equation (5) is particularly difficult to describe due to the heat transfer coefficient, which is a function of multiple variables. It depends, among other factors, on:

- flow velocity,
- flow character (laminar, transitional, turbulent),
- shape of the heat exchange surface,
- thermophysical properties of the fluid (density, specific heat, viscosity coefficient, thermal conductivity coefficient).

When a solid body is surrounded by a fluid, the effect of viscosity on flow becomes apparent near the wall. This is manifested by differences in flow velocity around the solid body's wall. The velocity increases as the distance from the wall surface increases, reaching a characteristic value of the flow of the entire fluid mass. The layer of fluid in close proximity to the wall, where significant velocities occur, is called the boundary layer.

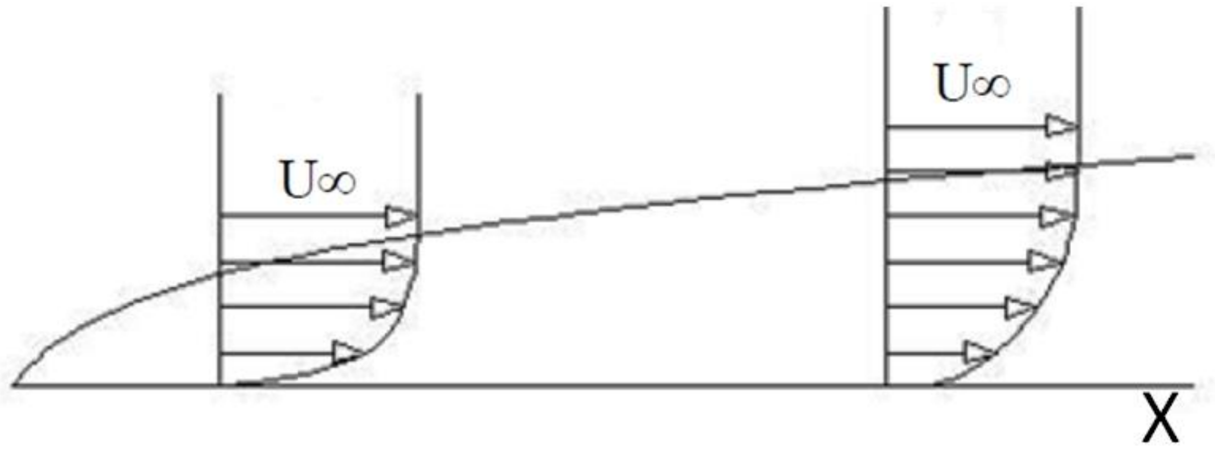


Fig. 1.2 Formation of the boundary layer

Figure 1.2 illustrates the process of boundary layer formation on a flat plate along which a fluid stream flows. The fluid velocity changes from 0 to $U_\infty$ at a large distance from the surface. The figure shows fluid profiles in various cross-sections of the stream above the plate, indicating an increase in the boundary layer thickness along the plate.

As mentioned above, the heat transfer coefficient is a function of many variables. A crucial factor is the nature of fluid flow. The flow can be laminar (layered) if the paths of moving fluid particles are parallel or turbulent (chaotic) when fluid particles move along intersecting paths, exhibiting, in addition to the main flow velocity, lateral movements with velocity components perpendicular to the main flow direction. The transition from laminar flow to turbulent flow occurs when the flow velocity exceeds the critical Reynolds number.

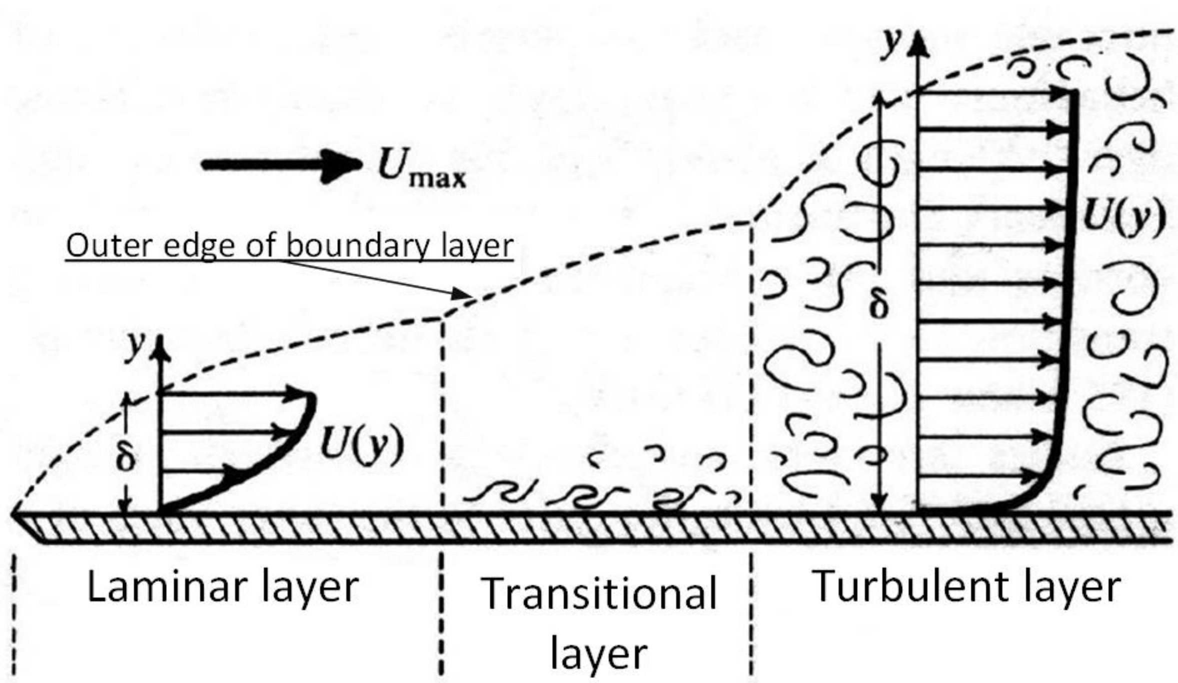


Fig. 1.3 Velocity distribution in the boundary layer

The reference temperature $T_{od}$ is specified for both the fluid and the channel wall.

For the fluid, the reference temperature $T_{od}$ is taken as the arithmetic mean of the extreme average fluid temperatures $T_{p,śr}$, whereas for the wall, it is the arithmetic mean of the extreme average temperatures of the channel wall $T_{s,śr}$.

The average temperature of the fluid in the cross-section of the flow channel is calculated by comparing the fluid's enthalpy determined in two different ways:

$$\int_A \rho c_p w\, T dA = T_{sr} \int_A \rho c_p w\, dA \;\rightarrow T_{sr} = \frac{\int_A \rho c_p w\, T dA}{\int_A \rho c_p w\, dA} \tag{21}$$

The reference temperature $T_{od}$ is given by:

$$T_{od} = \frac{1}{2}\left(T_{p,śr} + T_{s,śr}\right) \tag{22}$$

and is equal to the arithmetic mean of the average fluid temperature and the average wall temperature. It is a function of temperatures $T_p$ and $T_s$, which for high gas flow velocities takes the form:

$$T_{od} = T_\infty + \frac{1}{2}(T_s - T_\infty) + 0{,}22(T_r - T_\infty) \tag{23}$$

where:

- $T_\infty$ - fluid stagnation temperature outside the boundary layer $[\mathrm{K}]$,

- $T_s$ – wall surface temperature $[\mathrm{K}]$,

- $T_r$ – adiabatic wall temperature $[\mathrm{K}]$.

The adiabatic wall temperature is calculated from the formula:

$$T_r = T_\infty \left(1 + r\frac{\kappa - 1}{2}Ma^2\right) \tag{24}$$

where:

- $Ma$ – Mach number,

- $\kappa = \frac{c_p}{c_v}$ – isentropic index,

- $r$ – recovery factor of temperature.

The recovery factor *r* for Prandtl numbers ranging from 0.5 to 5 is the following:

- for a laminar boundary layer $r = \sqrt{Pr(T_{od})}$ $(25a)$
- for a turbulent boundary layer $r = \sqrt[3]{Pr(T_{od})}$ $(25b)$

## 2. THEORETICAL DETERMINATION OF HEAT TRANSFER COEFFICIENT

The laboratory setup allows for the investigation of the heat transfer coefficient in the case of perpendicular air jet impingement on the surface of the sample (Fig. 2.1). The calculation methodology was developed according to [2].

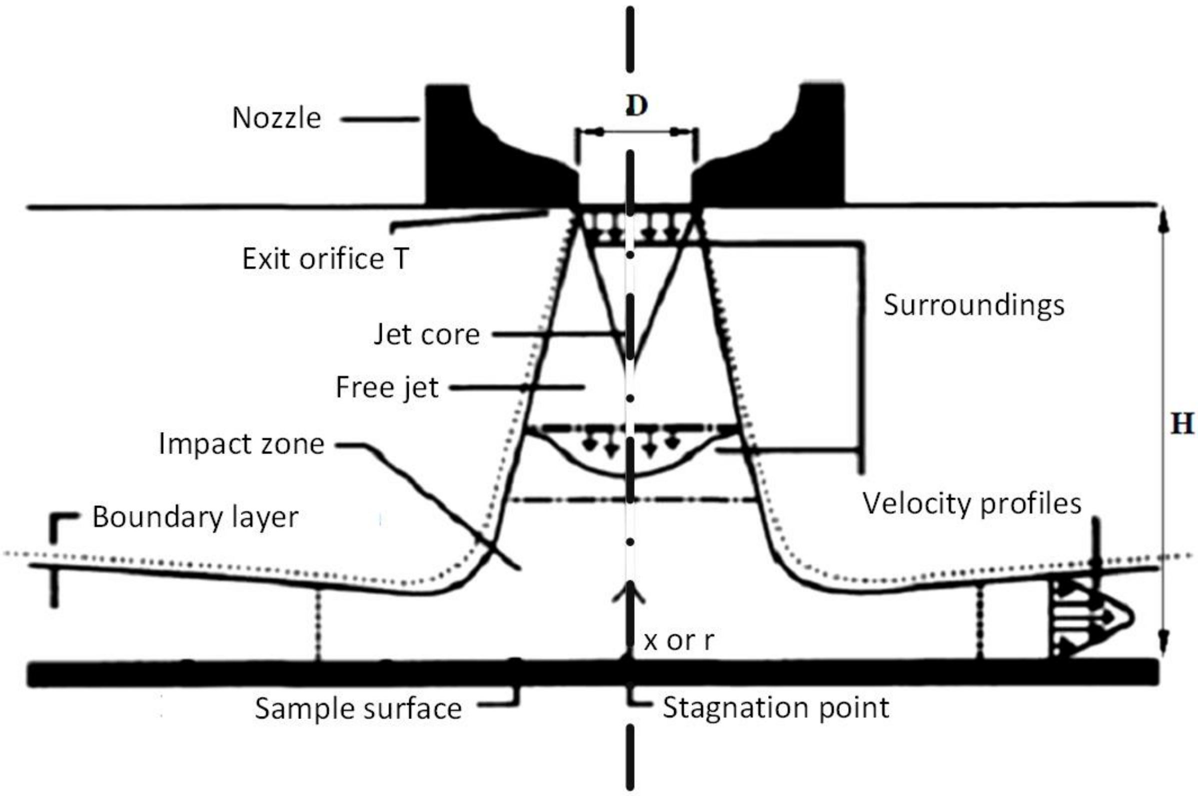


Fig. 2.1 Perpendicular Air Jet Impingement on the Surface

To determine the theoretical heat transfer coefficient, a general relationship should be applied using the Nusselt number:

$$\overline{Nu} = \frac{\alpha \cdot D}{\lambda_p} \tag{26}$$

The Nusselt number can be calculated theoretically or experimentally using similarity numbers. The average Nusselt number can be obtained by integrating local Nusselt values over the appropriate impact area of the air jet. The resulting correlations are presented in the following form:

$$\mathrm{Nu} = \mathrm{f}\left(\mathrm{Re},\ \mathrm{Pr},\ \mathrm{A_r},\ \frac{\mathrm{H}}{\mathrm{D}}\right) \tag{27}$$

where:

- $D = 0{,}005\ [\mathrm{m}]$ – diameter of the nozzle outlet,

- *H* – distance from the nozzle to the sample surface $[\mathrm{m}]$.

According to [12], the value of $A_r$ is expressed by the formula:

$$A_r = \frac{D^2}{4r^2} \tag{28}$$

were: *r* - radius of the sample surface.

To determine the Reynolds number and the Prandtl number, it is necessary to define the reference temperature and read the appropriate thermophysical parameters of dry air from tables [3]. The reference temperature is taken as the arithmetic mean of the air temperature measured before the sample surface and the temperature of the sample surface. With the appropriate values from the tables, the Reynolds number is calculated using the formula:

$$Re = \frac{vD}{\nu} \tag{29}$$

where:

- $v$ - velocity of the air stream $[\mathrm{m/s}]$,

- $\nu$ - kinematic viscosity of air $[\mathrm{m^2/s}]$.

The velocity of the air stream for the appropriate speed setting in the hot air station should be read from Table 2.1:

Table 2.1 Air stream velocity for a nozzle outlet placed 50 mm from the sample

| Speed Regulation Level | Air Stream Velocity $v$ [m/s] at 50 mm from Nozzle Outlet |
|---|---|
| 1 | 3,1 |
| 2 | 3,3 |
| 3 | 3,5 |
| 4 | 3,7 |
| 5 | 4,2 |
| 6 | 4,8 |
| 7 | 5,3 |
| 8 | 5,6 |

To determine the Nusselt number, the following correlation formula is used:

$$\frac{Nu}{Pr^{0.42}} = G\left(A_r, \frac{H}{D}\right)\left[2Re^{1/2}(1 + 0{,}005Re^{0.55})^{1/2}\right] \tag{30}$$

where:

$$G = 2A_r^{1/2}\frac{1 - 2{,}2A_r^{1/2}}{1 + 0{,}2\left(\frac{H}{D} - 6\right)A_r^{1/2}} \tag{31}$$

## 3. EXPERIMENTAL DETERMINATION OF THE HEAT TRANSFER COEFFICIENT

By equating Fourier's formulas (1) and Newton's formulas (5), we obtain the expression for the experimental calculation of the heat transfer coefficient:

$$\alpha = \frac{\lambda}{\delta}\frac{T_1 - T_2}{(T_S - T_2)} \tag{32}$$

where: $\delta$ – sample height.

The thermal conductivity coefficient for steel 1H18N9T is assumed to be: $\lambda = 14{,}5\left[\frac{\mathrm{W}}{\mathrm{m \cdot K}}\right]$.

## 4. LABORATORY SETUP

The setup for studying the heat transfer coefficient (Fig. 4.1) consists of:

1. A forced air flow system,
2. A cylindrical sample made of stainless steel 1H18N9T,
3. A data acquisition system from National Instruments,
4. A computer with LabVIEW SignalExpress software for data reading,
5. Two K-type sheathed thermocouples with an outer sheath diameter of 0.5 mm,
6. Two K-type thermocouples with thermoelectrode diameters of 0.05 mm.

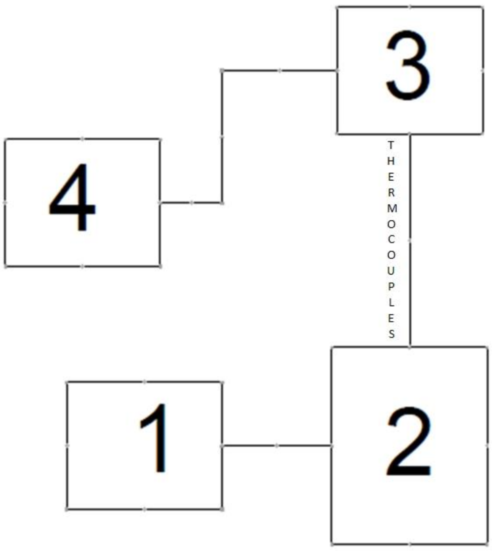


Fig. 4.1 Block diagram of measurement equipment

The air flow source is a HOT-AIR BK-858D soldering station (Fig. 4.2). It allows smooth regulation of the air stream up to $120 \left[\frac{L}{\min}\right]$ and temperature control from 100°C to 450°C. The device has an antistatic system that prevents damage to heated components. The installed nozzle has an inner diameter of 5 mm.

The sample is a 1H18N9T stainless steel 1H18N9T with the following dimensions:

1) Base radius: 20 mm,

2) Height: 20 mm.

Two K-type thermocouples are welded to the sample to measure the temperature on both front surfaces of the sample. The ambient temperature around the sample was measured using two additional sheathed K-type thermocouples placed in front of and behind the sample.

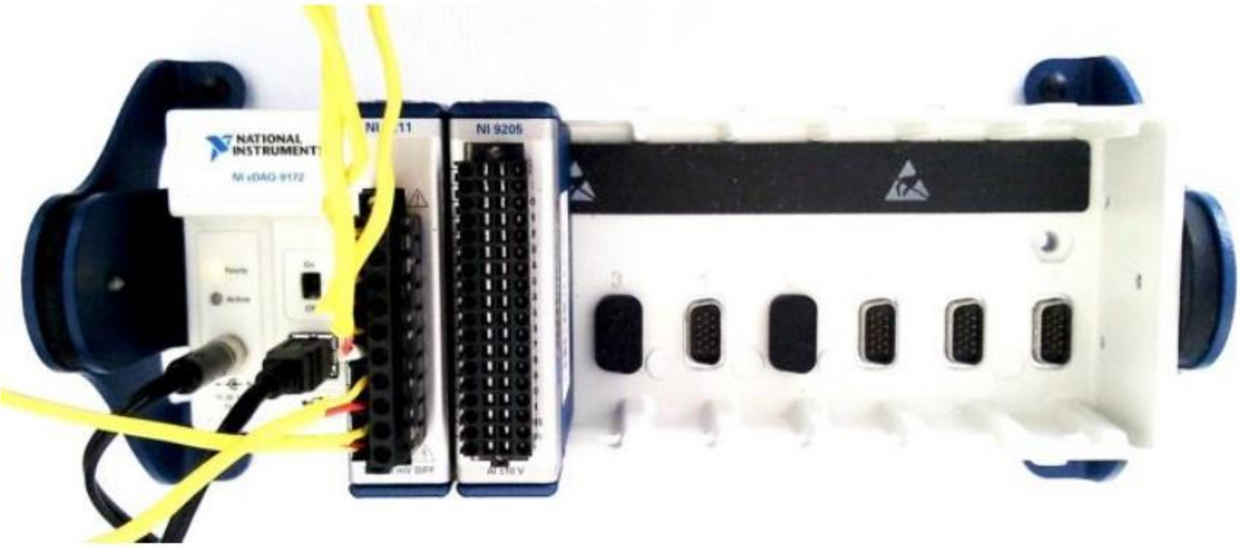

Fig. 4.2 Data Acquisition Module from National Instruments

Temperature measurement is performed using the measurement station equipped with a data acquisition module from National Instruments (Fig. 4.2). The NicDAQ – 9172 module allows the installation of eight different measurement cards. A special measurement card Ni – 9211, which has four wires with special connectors to connect thermocouples located in the test sample, is used for temperature measurement. The four thermocouples measure the following temperature values:

1. Temperature $T_1$ of the sample on the air stream side,
2. Temperature $T_2$ on the rear surface of the sample,
3. Ambient temperature $T_3$ on the air stream side (in front of the sample),
4. Ambient temperature $T_4$ behind the rear surface of the sample.

The Ni cDAQ – 9172 module should be connected to the power supply using an adapter and to the computer via a USB cable, which is equipped with National Instruments virtual measurement instruments.

The information collected by the NicDAQ – 9172 module is transferred to the computer. The software used for data reading is LabVIEW SignalExpress.

## 5. EXERCISE PROCEDURE

1. Connect thermocouple ends in the following order:

- $T_1$ - temperature of the sample on the air stream side,
- $T_2$ - temperature on the rear side of the sample,
- $T_3$ - ambient temperature on the air stream side (in front of the sample),
- $T_4$ - ambient temperature on the back side of the sample (behind the sample).

2. Start the LabVIEW SignalExpress software.

3. Enter the following control data:

- Thermocouple type: K (for all),
- Sample period: 1 s.

4. Perform the measurement series:

Series 1: Set the station temperature to 100°C, measure the distance from the nozzle outlet to the sample at 50 mm, and adjust the air stream velocity with the station knob (1, 2, 3, 4, 5, 6, 7, 8).

Series 2: Set the air stream velocity knob to level 1, measure the distance from the outlet of the nozzle to the sample at 50 mm, and adjust the station temperature (100°C, 150°C, 200°C).

Series 3: Set the station temperature to 100°C, set the air stream velocity knob to level 1, and adjust the distance from the nozzle outlet to the sample (50 mm, 40 mm, 30 mm, 20 mm, 10 mm).

5. Using Chapters 2 and 3, determine the following:

- Theoretical value of the heat transfer coefficient $\alpha_t$,
- Experimental value of the heat transfer coefficient $\alpha_p$.

## 6. CONTROL QUESTIONS

1. Describe the methodology for determining the theoretical heat transfer coefficient.
2. How do you determine the heat transfer coefficient from the measurements?
3. What do you understand by steady/unsteady heat transfer?
4. Describe the basic types of heat transfer.
5. Explain the concept of thermal conduction resistance.
6. Explain the phenomenon of heat penetration.

## REFERENCES

1. Wiśniewski S.: Wymiana ciepła, PWN Warszawa 1979.
2. Martin H., Heat and Mass Transfer between Impinging Gas Jets and Solid Surfaces. Academic Press, New York, 1977.
3. 3. [Engineering Toolbox: Air Properties] (http://www.engineeringtoolbox.com/air-properties-d_156.html)