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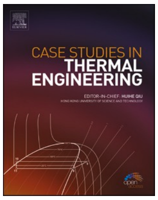

Experimental investigation on the temperature distribution within a cylindrical adiabatic container as time-dependent and conjugate

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ABSTRACT

In this study, the time dependent heating of a solid cylindrical body replaced within an isolated cylindrical container and reciprocally the simultaneous heating of the fluid (air/water) inside the container is experimentally investigated. For this purpose a double-walled cylindirical container of 25 cm diameter is prepared and isolated by using a 2 cm thick layer of styropor between the walls. An aluminium cylinder heated within some other adiabatic media then placed coaxially inside this container. Heat transfer problem socreated is assumed to be axially symmetric and accordingly the temperature measurements are taken at five stations on three horizontal straight lines all chosen to be on the same vertical plane passing through the common axis. At the end of the study, the following results were obtained: i) The equilibrium state between metal and fluid was reached in 120 min in air environment and 25 min in water environment. ii) It has been found that the cooling rate of the metal in the aqueous environment is approximately 5 times faster than the air environment. iii) The cooling and warming speed was faster in the first 30 min in the air environment and in the first 5 min in the water environment compared to the other time periods.

1. Introduction

The heat transfer conjugate is the mixture of all three or two heat transfer modes that exist simultaneously. It is a dynamic field of solid to solid joint, fluid to fluid, solid to fluid, and fluid to heat conversion of solid form. Analysis of the conjugate heat transfer mechanism in enclosures is critical because the chemical processes that exist in these enclosures are heavily temperature dependent [1, 2]. Typical examples of time-dependent heat transfer are the following: temperature distribution within the fin, the change in temperature in the steel within the water supply to the steel in an oil or water bath, as a result of the sudden change of gas temperature around the turbine blade after movement or stopping of a turbine, temperature distribution on the ground due to periodic changes of the heat transfer between the sun and the world. In these cases, calculation of thermal stresses in the material and determination of metallurgical conditions are very important. This is only possible by knowing the temperature distribution in the solid body.

Time-dependent regimes are divided into two classes: periodic and non-periodic regime. In the non-periodic regime, the temperature in the system changes as a general nonlinear function of time, but in the periodic regime, the temperature in the system shows a uniform or non-uniform but cyclical change. Non-uniform periodic changes can be represented by any cyclical function.

In some cases of non-periodic temperature changes, the temperature in the system decreases or increases until it reaches a certain equilibrium temperature. For example, if a steel heated in the furnace is suddenly immersed in a cold water bath, the temperature of

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Nomenclature

T	Temperature [K]
C_p	Heat Capacity [(J/KgK)]
ρ	Density [Kg/m^3]
h	Heat transfer coefficient between fluid and solid [W/m^2K]
t	Time [minute]
E	energy [J]
L	Cylinder length [m]
r	Cylinder radius [m]
A	Surface area [m^2]
V	Volume [m^3]

Subscripts

$_b$	initial temperature
$_\infty$	final temperature
stored	stored
outgoing	outgoing
Al	aluminum

the steel decreases over time, as a result of which the steel and water reach the same temperature. This type of time dependent heat transfer process is specially called transient regime. In this study, in the simplest form, the solid body and fluid come into contact suddenly at different uniform temperatures and one side loses heat while the other gains. Since the amount of heat in the insulated container does not change, such problems are identified by the name “Conjugate Heat Transfer”. As can be seen clearly, the conjugate heat transfer problem can be defined as the transition from one balance position to another balance position under the condition of constant heat quantity [3,4]. Similar studies conducted on the subject which are summarized below.

Malik et al. [1,2] presented in their studies an experimental as well as numerical study of conjugate heat transfer within an air filled bottom-heated vertical concentric cylindrical enclosure is presented. The results of an experimental study of the convective flows engendered within the annular gap between concentric vertical cylinders are presented by Ball et al. [3] Berbar et al. [4] solved the non-linear steady state heat conduction equation in a cylindrical conductor. Shiri [5] tried to develop a method to calculate the heat transfer coefficient between an aluminum bed and a liquid and investigated the temperature effect. Heat transfer coefficients were determined experimentally by Sparrow and Charme [6] for natural convection in the enclosed space between two vertical cylinders maintained at different uniform temperatures. Sarkar et al. [7] analyzed the analytical modeling of the temperature distribution both experimentally and numerically as a result of convective heat transfer in an anisotropic cylinder whose ambient temperature varies with time. Sammakia et al. [8] analyzed both experimentally and numerically the heat passing through natural convection from a flat vertical surface with thermal capacity to the adjacent external environment. In their study, Çukurel et al. [9] investigated the measurement of the jet impulse that transfers conjugate heat on a metallic plate of 15 mm thickness via a conduction-convection connection. Ejaz and Manzoor [10] conducted an experimental study of heat transfer in the vertical ring with a rotating inner cylinder heated from below. Nadeem and Sanjeev [11] addressed heat transfer in two dimensions by convection in a rotating cylinder. Kubair and Simha [12] numerically studied natural convection heat transfer between the inner wall with separate heat sources and a cylindrical ring-shaped space. Keyhani and Kulacki [13] studied heat transfer by convection between the heated inner wall and the vertical ring. Jones [14] worked numerically in a transient regime, heating a vertical wall of a rectangular thermosiphon with a constant heat flow (“warmup”) or cooling it by convection to the environment (“cooldown").

As it can be seen in the examples mentioned above, the temperature distribution in the metal and the time to reach equilibrium in the conjugate temperature change due to time between the metal and the fluid are significant in terms of calculation of thermal stresses and determination of metallurgical conditions. Additionally, studies to increase the storage capacity of latent heat in thermal energy storage units, average discharge and charging power raise the significance of the subject.

In the test carried out oriented at this objective, a heated aluminum cylinder is placed inside the cylindirical adiabatic container containing air or water, until it warms up to a certain temperature and reaches a homogeneous temperature. The conjugate temperature change between aluminum and fluid was measured at 15 different stations depending on time and by the temperature distribution in the solid and fluid medium the time to reach equilibrium was determined experimentally.

2. Experimental set up

The experiment set shown in Fig. 1 was prepared for the problem of heat distribution between metal and fluid at different temperatures in a fluid-filled adiabatic container. The container consists of two cylindrical containers, the inside diameter of which is 22 cm and the inside height is 30 cm, which are intertwined with 2 cm stropor. The heated metal is aluminum material with a diameter of 10 cm and a length of 30 cm. For the experiments, the cylindrical metal and container axes coincided, and 2 measuring stations in metal and 3 in the fluid were prepared on a plane passing through a common axis. Thermocouples were connected to a total of 15

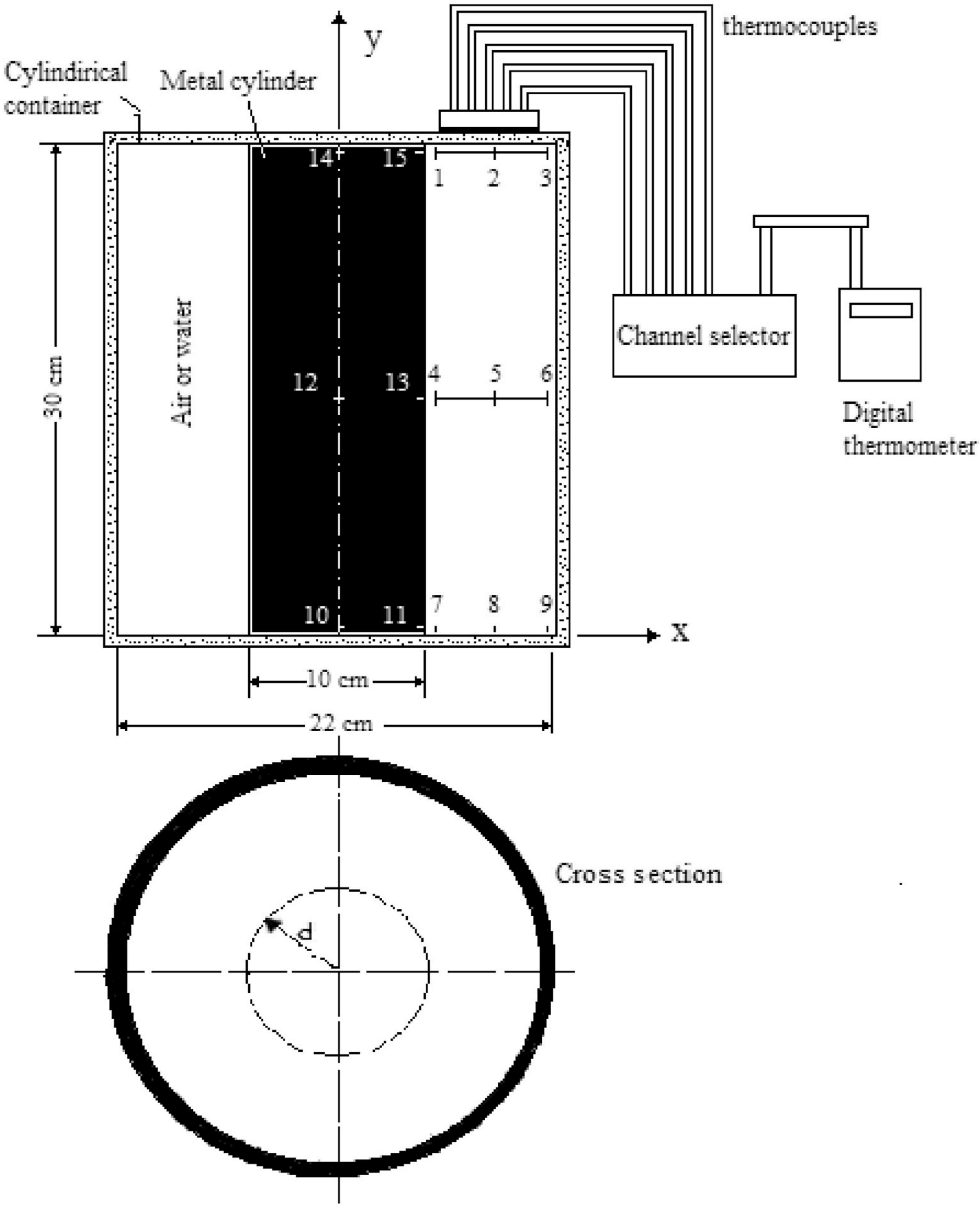

Fig. 1. Cross-sectional view of experimental set up.

measuring stations. The other ends of the thermocouples were connected with the channel selector and temperatures were read directly from the digital thermometer (Fig. 1).

During the experiments, the heating of the metal was provided by an electric heater in a separate adiabatic container. Measurements were made for heated metal-air and heated metal-water conjugate temperatures.

The measurement station numbers in cylindrical aluminum and container are as follows:

For vertical axis y: 0 cm codes 10, 11, 7,8,9.

y:15 cm codes: 12, 13, 4,5,6
y:30 cm codes: 14,15, 1, 2, 3 stations are involved

2.1. Calculation of the time-dependent temperature change

An infinitely long radius cylinder is cooled by immersing it in an environment where fluid is present at T∞ temperature at the initial

Table 1
Temperature values of the station 15 as time dependent, calculated in the air or water environment (oC).

Fluid/Time (minute)	0	30	60	90	120
Air	42	38.99	37.38	36.51	36.45
Water	42	30.86	26.27	24.04	23.16

T_b temperature. Considering that the temperature changes only in the r direction and depending on time, there is no heat generation in the system, the energy equation is as follows. (The energy equation can be written in the form of Equation (1), since the reduction in energy stored in the cylinder will be equal to heat transfer with the transport from the surface of the object to the medium).

$$-E_{stored} = E_{outgoing} \tag{1}$$

The decrease in stored energy can be written as Equation (2):

$$E_{stored} = m.Cp.V.(dT/dt) \tag{2}$$

Transfer of heat from the surface of the object can be written in Equation (3) using Newton's law of cooling:

$$E_{outgoing} = h.A.(T- T_{\infty}) \tag{3}$$

equations (2) and (3) are placed in equation (1). Using the boundary conditions, the heat conduction equation is written as Equation (4):

$$T(t) = T_{\infty} + (T_b - T_{\infty}).e^{-m..t} \tag{4}$$

Here, the value of "m" can be calculated by Equation (5)

$$m = \frac{A.h}{\rho.C_p.V} \tag{5}$$

Equation (3) can be written in the following way, considering the roller as an infinite cylinder, ignoring the heat losses in the upper and lower circular areas. If the transport coefficient between aluminum and air $h = 250\ W/m^2\ ^oC$, $\rho_{Al} = 2702\ kg/m^3$, $C_{pAl} = 896\ J/kg\ ^oC$ and $L = 0.03$ m values are calculated as follows, the following result is obtained:

$$m = \frac{A.h}{\rho.Cp.V} = \frac{h}{\rho.Cp.L}$$

$$m = \frac{250}{2702.896.0,03} = 3,442.10^{-5}$$

In the case of fluid water, the coefficient of transport between aluminum and water is calculated as $m = 4.70.10^{-5}$ by taking $h = 800\ W/m^2\ ^oC$.

As an example solution, the equation giving the temperature distribution for the 14–15 stations can be calculated as follows: Making the required calculations, where the fluid air is $T_b = 42\ ^\circ C$, $T_{\infty} = 35{,}5\ ^\circ C$, $m = 3442.10^{-5}$ using Equation (2);

$$T(t) = 35,5 = (42 - 35,5).e^{-3,442.10^{-5}.t}$$

And for liquid: $T_b = 42\ ^\circ C$, $T_{\infty} = 22{,}5\ ^\circ C$ $m = 4{,}70.10^{-5}$

$$T(t) = 22,5 + (42 - 22,5).e^{-4.70.10^{-5}.t}$$

You can see the results on Table 1 for time-dependent temperature values of Station no 15:

2.2. Heat balance of the system

The thermal equilibrium calculation of the experimental system was applied as an example to the heated metal-water conjugation problem.Where aluminum metal and water are written using Equations (6) and (7) at the temperature of 41 °C at t = 0 and balance temperatures of 19.5 °C at t = 25,

$$Q_{metal} = \pi.d^2.L.\rho.C_p\Delta T/4 \tag{6}$$

$$Q_{metal} = \pi.d^2.L.\rho.C_p.\Delta T/4 \tag{7}$$

$T = 0$ dk $Q_{Ometal} = 3{,}14.(0{,}10)^2.\ 0{,}3.2700.0{,}896.41/4 = 233{,}58$ kj

$Qo_{owater} = 3{,}14.(0{,}22^2 – 0{,}10^2).\ 0{,}3.999.4{,}18.17/4 = 641{,}96$ kj
Total heat = 233,58 + 641,96 = 875,54 kJ

Table 2
Temperature distribution of the stations at different times (heated metal-air), (°C).

Time (minute)	horizontal axis (x), (cm)					Station no
	0	5	6	7.5	11	
0	42	42	18	18	18	14, 15, 1, 2, 3 (y = 30 cm)
30	41	40	25	24	23	
60	39	38	29	28	26.5	
90	37	36.5	30	29	28	
120	36	35.5	33	32.5	32	
0	42	42	18	18	18	12, 13, 4, 5, 6 (y = 15 cm)
30	40	39	24	23	23	
60	38.5	37	28	27	26.5	
90	36.5	36	29	28.5	28	
120	35.5	35	32.5	32	31.5	
0	42	42	18	18	18	10, 11, 7, 8, 9 (y = 0 cm)
30	39.5	39	24	22.5	22	
60	38	37	27	26.5	26	
90	36	35.5	28	28	27.5	
120	35	34.5	32	31.5	31	

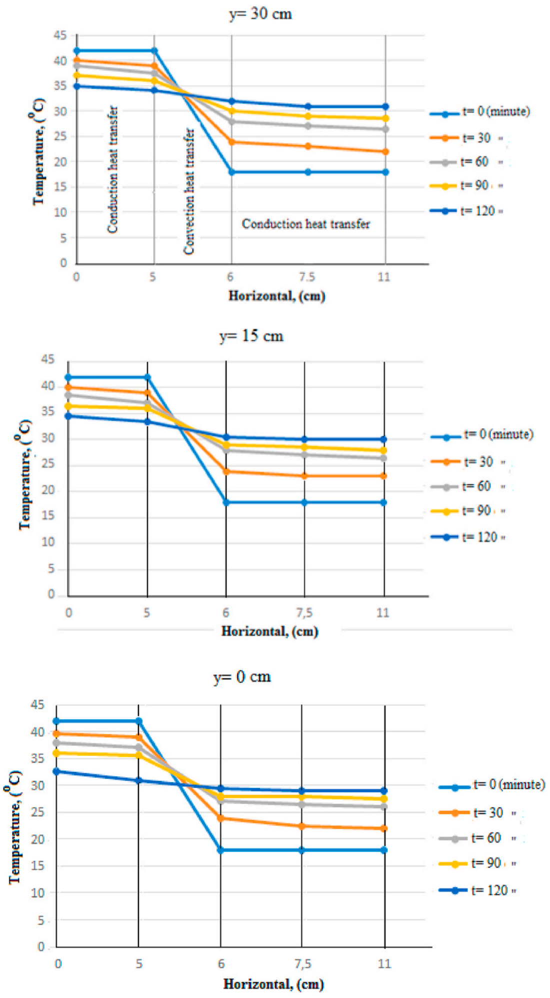

Fig. 2. Heated metal-air conjugate temperature change in adiabatic container.

Table 3
Heated metal-water conjugate temperatures of the stations, (°C).

Time (minute)	horizontal axis (x), (cm)					Station no
	0	5	6	7.5	11	
0	42	42	17	17	17	14, 15, 1, 2, 3 (y = 30 cm)
5	30	29.5	19.5	19	18	
10	28	26	20.5	20	19	
20	26	24	21	20.5	19.5	
25	23.5	22.5	22	21.5	21	
0	42	42	17	17	17	12, 13, 4, 5, 6 (y = 15 cm)
5	29.5	28	19	18.5	18	
10	27.5	25.5	20	19	18.5	
20	25.5	23.5	20.5	20	19	
25	22.5	22	21.	20.5	20	
0	42	42	17	17	17	10, 11, 7, 8, 9 (y = 0 cm)
5	29	28	18.5	18	18	
10	26.5	25	19.5	18.5	18.5	
20	25	24	20	19.5	19	
25	22	22	20.5	20.5	20	

Table 4
Experimental and calculated values of the final temperature of the cylinder surface in the air environment.

Time (minute)	Aluminum-air		Station no
	Calculated	Experimental	
0	42	42	15
30	38.99	40	
60	37.38	38	
90	36.51	36.5	
120	36.45	35.5	
0	42	42	13
30	38.76	39	
60	37.02	37	
90	36.09	36	
120	35.58	35	
0	42	42	11
30	38.53	39	
60	36.67	37	
90	35.66	35.5	
120	35.13	34,5	

$T = 25$ dk $Q_{25\ \mathrm{metal}} = 3{,}14.(0{,}10)^2.\ 0{,}3.2700.0{,}896.19{,}5/4 = 111{,}09$ kj

$Q_{25\ \mathrm{metal}} = 3{,}14.(0{,}22^2 – 0{,}10^2).\ 0{,}3.999.4{,}18.19{,}5/4 = 716{,}95$ kj
Total heat = 111,09 + 716,95 = 828,04 kJ
Loss rate = (875,54–828,04)/875,54 = 0,054 veya %5.4 dür.

3. Conjugate temperature change

3.1. *Hot metal-air conjugate temperature change inside the air filled container*

The aluminum cylinder was heated in another adiabatic container for the tests so that a consistent temperature distribution was obtained at 42 °C and the bottle cap was closed at 18 °C after it was put in the tube. In the change of hot metal-air conjugate temperature, the temperature of the equilibrium was reached in about 120 min by cooling the metal in the air-filled container and warming up the gas. The results of the measurements are shown in Table 2 and changes in temperature over time are shown in Fig. 2.

3.2. *Hot metal-water conjugate temperature change in a water filled container*

In the heated metal-water conjugate temperature change, after the metal at 42 °C was placed in a container filled with water at 18 °C, the equilibrium state was quite close by cooling the metal and heating the water in approximately 25 min. Measurement results are given in Table 3 and temperature changes over time are shown in Fig. 4.

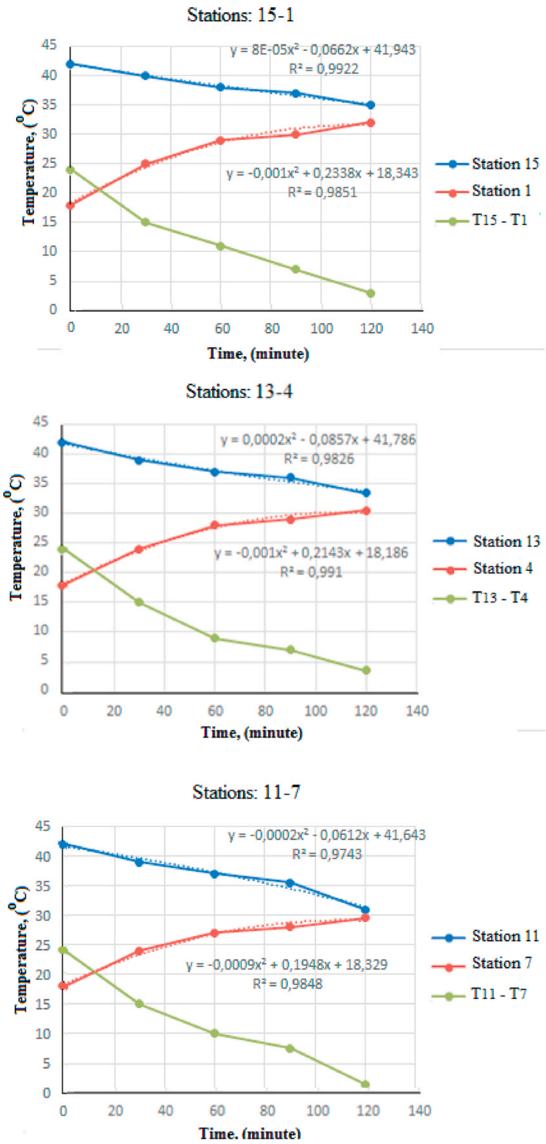

Fig. 3. Cooling-heating and differential temperature change of metal and air.

4. Results and discussions

The following findings were obtained concerning the equivalent temperature change applied for the fluid environment (air/water) with aluminum at different temperatures.

As seen in Table 2, the final temperatures of cooling, measured at the stations inside the metal, vary between 34.5 and 36 °C and the stations inside the air between 31 and 33 °C. Approximately 0.5 °C difference is determined between the temperatures of the stations on the metal middle vertical axis (station numbers 10, 12, 14) and the station temperatures on the metal surface (station number 11, 13, 15). Similarly, a difference of approximately 1 °C was determined between the temperatures of the vertical axis line (number 1, 4, 7) touching the metal surface in air filled volume and the station (3, 6, 9) temperatures in the axis direction close to the container wall. In Table 4 and Fig. 2, time-dependent temperature changes in the measurement stations with solid body and fluid (air) can be seen. Examining the figure itself, it can be understood that the fluid heats up while the metal cools depending on the time and the equilibrium state is achieved after about 120 min. Moreover, it is seen that the cooling and warm-up rate in the first 30 min is faster than other time periods. Depending on the time for the heated metal-air conjugate temperature change, the cooling curves of the metal on the contact surfaces of the metal and the fluid and the temperature curves and the difference temperature curves are shown in Fig. 3.

As seen in Table 3, the cooling final temperatures measured at the stations in the metal range between 22 and 23 °C and the heating final temperatures at the stations in the water vary between 20 and 22 °C.

While the difference between the x = 0 cm vertical axis stations of the metal and the station (metal surface) temperatures of the x =

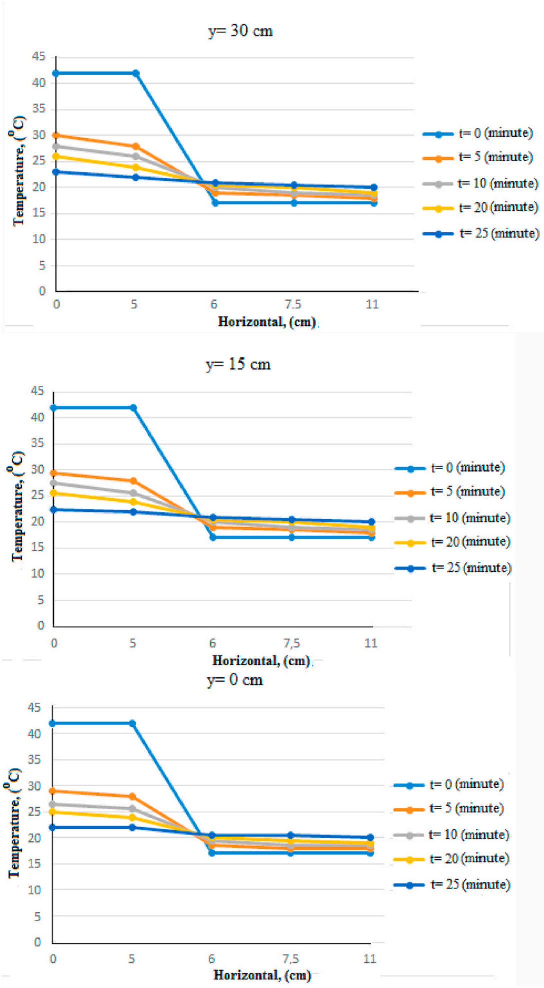

Fig. 4. Heated metal-water conjugate temperature change in adiabatic container.

Table 5
Experimental and calculated values of the final temperature of the cylinder surface in the water environment.

Time (minute)	Aluminum-water		Stations no
	Calculated	Experimental	
0	42	42	15–1
5	30.86	29.5	
10	26.27	26	
20	24.04	24	
25	23.16	22.5	
0	42	42	13–4
5	30.58	28	
10	25.87	25.5	
20	23.58	23.5	
25	22.68	22	
0	42	42	11–7
5	30.58	28	
10	25.87	25	
20	23.58	23	
25	22.68	22	

5 cm vertical station, the final time is approximately 1 °C, there is a difference of 1–1.5 °C in the water filled volume x = 6 cm and x = 11 cm.

Depending on the time for the heated metal-water conjugate temperature change, the cooling of the metal on the contact surfaces of

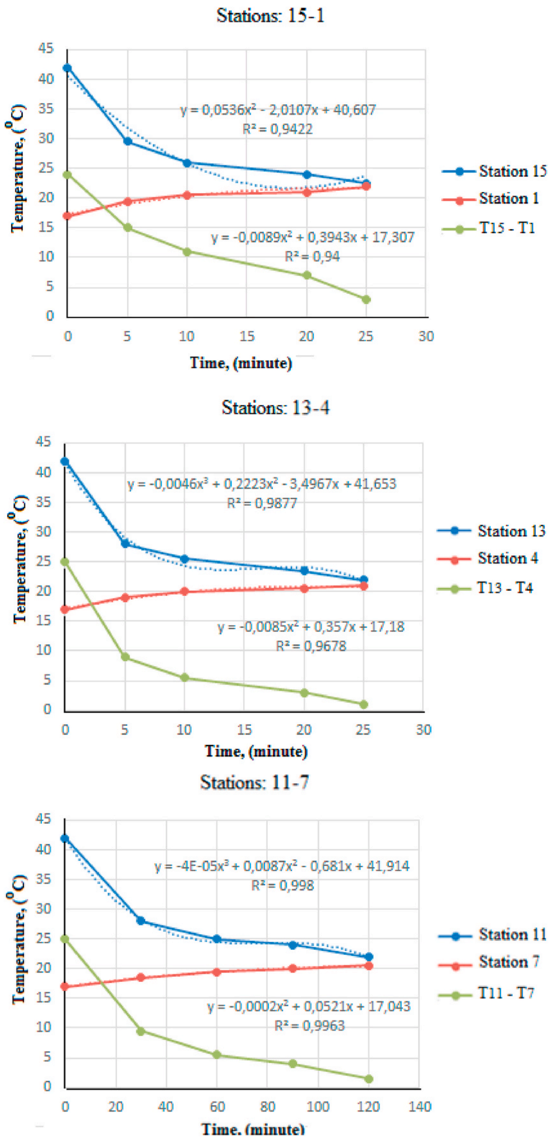

Fig. 5. Metal and water cooling-heating and differential temperature change.

the metal and the fluid-the warming of the water and the difference temperature curves are shown in Table 5, Figs. 4 and 5. Examining Fig. 4, it can be seen that, The time to reach the equilibrium state is 25 min and heating rate in the first 5 min is faster than other time periods.

In the process of reaching the equilibrium state, metal (station number: 14 and 15) cools by 14.5% and 15.5%, while the air environment (station number 1, 2 and 3) warms up to 83.3%, 80.5% and 77.7%, thus reaching the equilibrium temperature. While the same stations caused cooling by 44.5% and 46.4% in metal for the water environment, 29.4%, 26.4% and 23.5% of heating was reached, thus achieving the equilibrium temperature in the stations within the aquatic environment.

4.1. Statistical analysis

The constants in models were determined by the nonlinear regression analysis to examine the goodness-of-fit the models. Statistical software package [15] was used to perform the nonlinear regression analysis of experimental thermal conductivity data. The quality of the fit of the model was estimated using the various statistical parameters such as root mean square error (RMSE), chisquare $\times^2$, mean bias error (MBE), mean percentage error (MPE) and the coefficient of determination r^2. These parameters can be calculated as follow:

Table 6
Statistical test results.

Station no	Time (minute)	RMSE	Chi-square	MBE	R2
Aluminum-Air					
15	30	1.5812	3.3335	0.0100	0.9987
	60	1.6070	1.8159	0.2550	0.9727
	90	0.4360	0.2535	0.1350	0.9552
	120	0.6538	0.5700	0.0750	0.9512
13	30	1.5992	1.4101	−0.2400	0.9838
	60	1.3192	2.3203	−0.2300	0.9751
	90	1.0040	1.3441	0.0900	0.9900
	120	0.5444	0.3952	0.0825	0.9910
11	30	0.8578	0.9812	0.2200	0.9838
	60	0.7803	0.8119	0.3300	0.9751
	90	0.8807	1.0341	0.1600	0.9820
	120	0.6220	0.5159	0.0925	0.9894
Aluminum -Water					
15	5	0.7397	0.7295	−0.0150	0.9883
	10	0.4392	0.2572	0.1450	0.9779
	20	0.3558	0.1688	0.0400	0.9933
	25	0.9059	1.0941	−0.0900	0.9844
13	5	0.3625	0.1752	0.0800	0.9895
	10	0.2773	0.1025	0.1200	0.9814
	20	0.3023	0.1219	0.1700	0.9711
	25	0.3023	0.1219	0.1700	0.9860
11	5	1.1209	1.6752	0.0800	0.9895
	10	0.9093	1.1025	0.1200	0.9814
	20	0.7674	0.7852	0.2050	0.9652
	25	0.6383	0.5432	0.1800	0.9682

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(k_{exp,i} - k_{pre,i}\right)^2\right]^{1/2}$$

$$\times^2 = \sum_{i=1}^{N}\frac{\left(k_{exp,i} - k_{pre,i}\right)^2}{N - n}$$

$$MBE = \sum_{i=1}^{N}\frac{\left(k_{pre,i} - k_{exp,i}\right)}{N}$$

Where $k_{exp,i}$ is the experimental thermal conductivity, $k_{pre,i}$ is the predicted thermal conductivity, N is the number of data points and n is the number of model parameters.

The statistical test results regarding the temperature measurements at the stations are shown collectively in Table 6.

5. Conclusion

While the heated cylindrical metal made of aluminum material has a uniform temperature, it is cooled by separately leaving it to the air and water environment, while the conjugate temperature changes of the metal and fluid are examined and the following points are determined:

- ✓ When the cylinder, which is heated up to an average temperature of 42 °C, is left to be cooled in the air environment in the adiabatic container at 17–18 °C, an almost stable result was obtained by getting to the related metal and air temperatures within 120 min. In this period of time, while the outer surface of the aluminum cylinder cools down from 42 °C to 35.5 °C along the vertical axis (y: 30 cm code), respectively, the air environment heated up from 17 °C to 33, 32.5, 30 °C, respectively, along the horizontal axis (x: 6, 7.5 and 11 cm).
- ✓ If the cylinder, which is heated up to 42 °C, is placed in an adiabatic container filled with 17 °C water, it takes 25 min to reach equilibrium at the conjugate temperature change.

While the aluminum cylinder's outer surface along the vertical axis (at the code of y: 30 cm) cools from 42 °C to 22.5 °C respectively, the water environment heated up from 17 °C to 22, 21.5, 21 °C, respectively, along the horizontal axis.

- ✓ It was determined that the cooling rate of the metal was approximately 5 times faster in the aqueous environment than in the air.
- ✓ The cooling and warming speed was faster in the first 30 min in the air environment and in the first 5 min in the water environment compared to the other time periods.

Author statement

Throughout this work, the responsibility belongs to the author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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