Acta Tecnología - International Scientific Journal about Technologies
Volume: 6 2020 Issue: 1 Pages: 5-14 ISSN 2453-675X

doi:10.22306/atec.v6i1.72

Received: 03 Mar. 2020
Accepted: 26 Mar. 2020

THE POSSIBILITY OF USING PCM SLURRY AS A CIRCULATING MEDIUM IN A HEATING SYSTEM – MODEL TESTS

Tomasz Janoszek
Central Mining Institute, plac Gwarków 1, 40-166 Katowice, Poland, EU, tjanoszek@gig.eu

Keywords: numerical model, PCM, slurry, CFD

Abstract: The aim of the article is to develop a numerical model in order to compare the classic heating system with a heating system where PCM slurry constitutes the heat-transfer medium. Physical parameters such as PCM slurry specific heat, viscosity and thermal conduction are required in order to generate the numerical model. PCM producers do not possess the required data, so the performance of specialist tests in outside institutions is necessary in order to obtain these values. PCM materials are substances with high heat of fusion values. During fusion or solidification at a specific temperature, they accumulate or release high amounts of energy. The numerical model consists of two parts that make it possible to compare various heat-transfer media (water and PCM slurry). The model tests encompass the simulation of parameters and their variations for a system utilising water and utilising the PCM slurry at their various concentrations. The tested parameters are variations of slurry temperature at the heat exchanger outlet, depending on the PCM concentration in the slurry. Among the many testing methods, it was decided to analyse the presented solution using the computational fluid dynamics (CFD) method. Analysed test subject numerical solution geometry and discretisation area were discussed, as well as numerical model assumptions and parameter values for the developed PCM slurries.

1 Introduction

In last decade most recent researchers are focused on improve energy efficiency with use of latent heat thermal storage materials such as phase change materials (PCM) [1,2]. This interest was derived growth of need in materials having the ability to thermal energy storage. PCM are characterized by a number of parameters which are interrelated such as: density, specific heat, thermal conductivity, which increase capacity to absorption and emission of large amount of heat during physical state change process due to higher heat density [6]. Higher heat density directly determines PCM ability to heat thermal storage [3-5,7].

The analysed research problem comes down to describe the possibility to use phase-change materials (PCM) as substances improving the efficiency of a selected heat exchanger, based on numerical simulations. Positive results of numerical calculations may contribute to a decrease of the heat exchanger surfaces as well as a decrease in the amount of fuel supplied to the heat source, which may translate into profits for heat storage system users, generally to minimize power consumption in heating system basing on water [8-12].

It was decided to conduct the numerical analysis using the computational fluid dynamics (CFD) method in the Ansys-Fluent program, based on the numerical model simulating the transfer process of the PCM slurry at a volume reflecting the fluid geometry. Ansys-Fluent is an extraordinarily efficient and modern tool that minimises the expenditure required to study a subject during the initial stage of a project, while simultaneously enabling the control and verification of many variants of possible variables. The obtained numerical solution made it possible to compare a classic heating system with a heating system where PCM slurry constituted the heat-transfer medium. In order to generate a numerical model, laboratory tests were conducted to determine the slurry specific heat, viscosity and thermal conduction at various PCM concentrations [18-19].

The numerical model data were obtained from literature, practical knowledge and substance physical property tabular data as well as from conducted tests of phase-change substance physical properties (PCM slurry specific heat, viscosity and thermal conduction).

The developed numerical model was divided into two parts enabling the prediction and comparison of various heat-transfer media. The first part encompassed the simulation of parameters and their variations for a standard system utilising water. Whereas the second part simulated the same parameters and their variations for a system utilising PCM slurry at various concentrations. Variations of slurry temperature at the heat exchanger outlet constituted the tested parameters [20-21].

2 Material and method

2.1 Laboratory test

Phase-change materials (PCM) are active phase-change compounds encapsulated within an impermeable polymer membrane in the form of a capsule with a size of 5-50 µm. The aim of such action is to completely separate and secure them from environmental influence. Under specific ambient temperature conditions, they accumulate or release large amounts of energy at a nearly constant temperature corresponding to the phase transition temperature of the phase-change material (PCM) [2-5].

Mixtures in the form of dispersions based on water with no mineral salts with the addition of a phase-change material (PCM) in the amount of 10%, 20% and 30% were prepared for realisation purposes. The PCM slurry preparation stages were presented schematically in Figure 1.

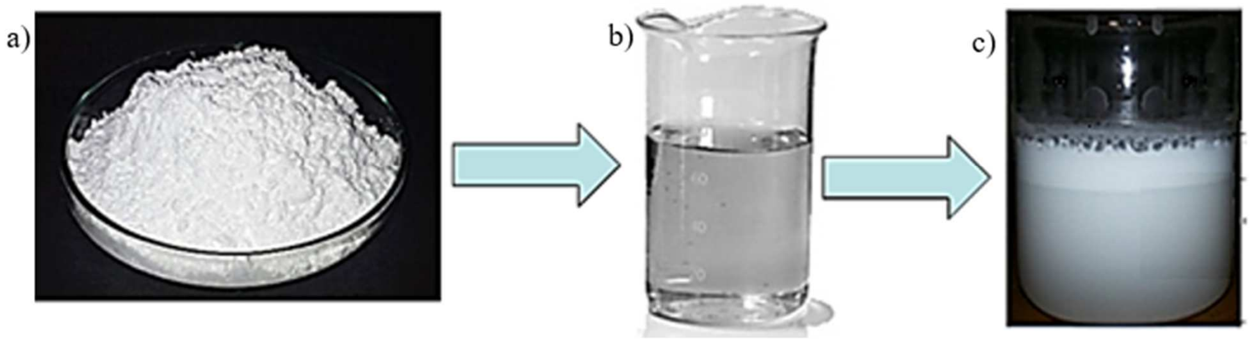

Figure 1 PCM slurry preparation stages: a)- PCM, b)- distilled water, c)- PCM slurry [2,6]

Individual PCM slurry samples underwent testing under laboratory conditions in order to determine the average values of such parameters as:

- specific heat using a Netzsch STA 409 PC Luxx thermal analysis device (Figure 2), simultaneous thermogravimetric and calorimetric analyses from 20°C into the temperature range of 1650°C,

Figure 2 STA 409 PC Luxx Simultaneous thermal analyser [13]

- thermal diffusion using a Netzsch LFA 457 analyser (Figure 3), allows measurements from -125°C to 1100°C with measuring range 0.01 mm2s-1 to 1000 mm2s-1 for thermal diffusivity and measuring range 0.1 Wm-1K-1 to 2000 Wm-1K-1 for thermal conductivity,

Figure 3 Netzsch LFA 457 analyser [14]

- dynamic viscosity using a TA Instruments AR2000ex rheometer (Figure 4).

Figure 4 TA Instruments AR2000ex rheometer analyser [15]

The defined physical property values directly determine the application of a heat-transfer medium in a heating system. The obtained investigated parameter values constituted the input data for the developed numerical model.

Acta Tecnología – International Scientific Journal about Technologies
Volume: 6 2020 Issue: 1 Pages: 5-14 ISSN 2453-675X

2.1.1 Result

In Figures below was shown the results of laboratory measurements of PCM slurry parameters depending on temperature changes such as:

- influence of temperature changes on the PCM slurry viscosity shown in Figure 5,
- influence of temperature changes on the PCM slurry thermal diffusivity shown in Figure 6,
- influence of temperature changes on the PCM slurry specific heat shown in Figure 7.

The obtained results were subjected to regression analysis with the intention of determining the equation reflecting the variability of the tested PCM slurry parameters. An effect of the activity's equations describing variability of parameters of PCM slurry such as specific heat, viscosity and thermal diffusivity in the range of temperature changes from 20ºC to 85ºC in the following form:

a) for 10% PCM slurry:
   - dynamic viscosity correlation was obtained in form of $y = 0.0001x + 0.0214$,
   - thermal diffusivity correlation was obtained in form of $y = 3e^{-6}x^5 – 0.0009x^4 + 0.1132x^3 – 7.3426x^2 + 236.17x – 3010.9$,
   - specific heat correlation was obtained in form of $y = 5e^{-5}x^6 – 0.0133x^5 + 1.5989x^4 - 101x^3 + 3536.5x^2 - 64973x + 491153$ for T< 71.2ºC and $y = 0.0007x^6 - 0{,}344x^5 + 70.756x^4 – 7758.8x^3 + 478354x^2 - 2e^7x + 2e^8$ for T ≥ 71.2ºC.

b) for 20% PCM slurry:
   - dynamic viscosity correlation was obtained in form of $y = 0.0009x + 0.1191$,
   - thermal diffusivity correlation was obtained in form of $y = 5e^{-7}x^5 – 0.0002x^4 + 0.0256x^3 – 1.754x^2 + 59.071x – 781.62$,
   - specific heat correlation was obtained in form of $y = 0.0001x^6 - 0{,}0389x^5 + 4.6538x^4 – 292.89x^3 + 10227x^2 - 187780x + 1e^6$ for T< 71.2ºC and $y = 0.0037x^6 – 1.8287x^5 + 373.7x^4 - 40704x^3 + 2e^6x^2 – 8e^7x + 1e^9$ for T ≥ 71.2ºC.

c) for 30% PCM slurry:
   - dynamic viscosity correlation was obtained in form of $y = 0.003x + 0.4368$,
   - thermal diffusivity correlation was obtained in form of $y = -4e^{-6}x^5 + 0.0014x^4 – 0.1727x^3 + 10.939x^2 – 343.2x + 4268.2$,
   - specific heat correlation was obtained in form of $y = 0.0002x^6 – 0.0464x^5 + 5.5057x^4 – 343.14x^3 + 11852x^2 - 215037x + 2e^6$ for T< 71.2ºC and $y = 0.0082x^6 – 3.9909x^5 + 812.11x^4 - 88095x^3 + 5e^6x^2 – 2e^8x + 2e^9$ for T ≥ 71.2ºC.

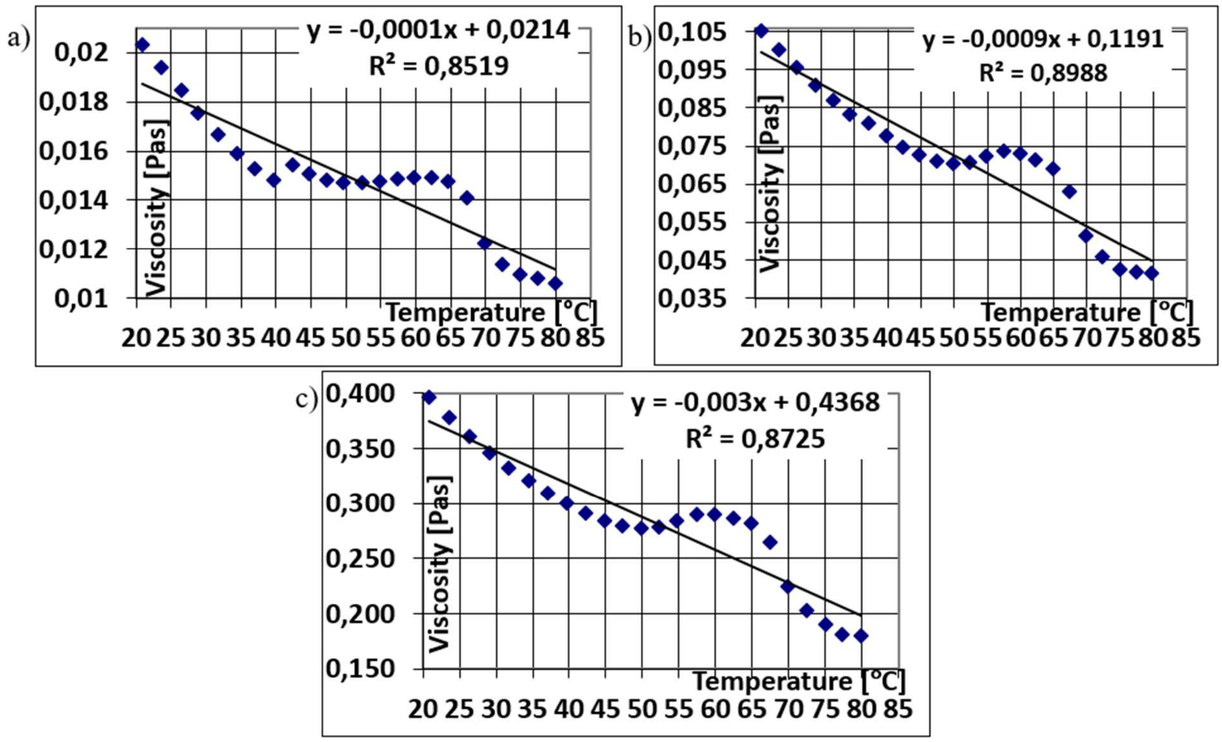

Figure 5 Influence of temperature on the dynamic viscosity of PCM slurry: a) – 10% PCM, b) – 20% PCM, c) – 30% PCM

When the ambient temperature of PCM slurry increases, the dynamic viscosity of the mixture decreases can be observed. Additionally, it can be observed that with increasing the concentration of PCM in the mixture, the dynamic viscosity of the PCM slurry a significant growth.

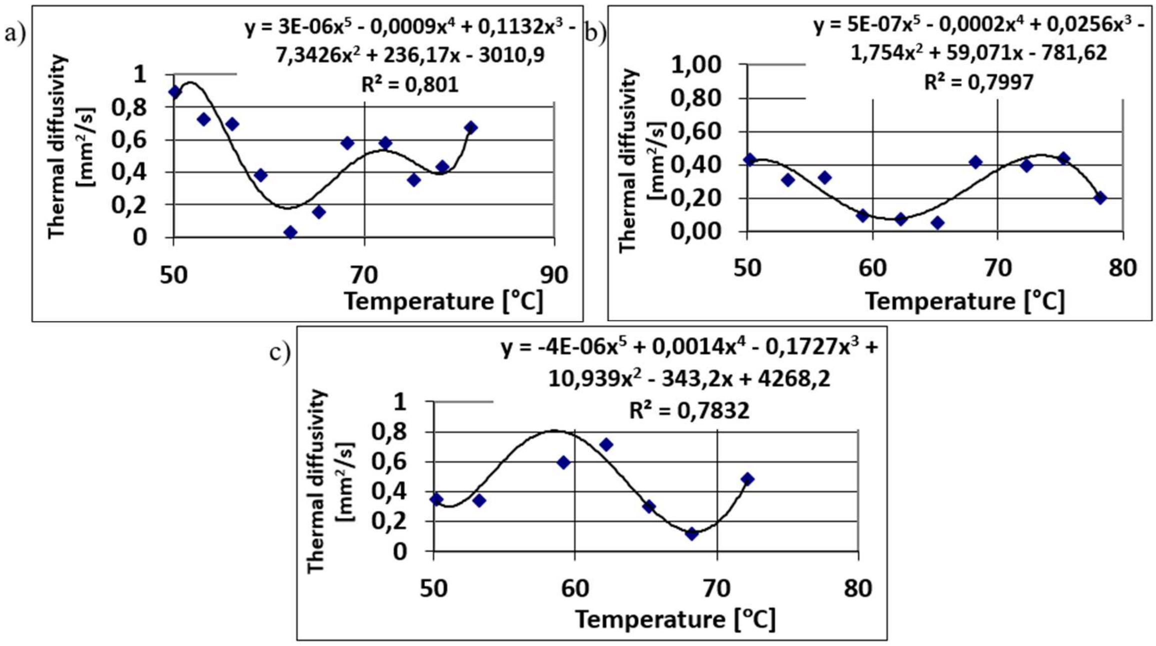

Figure 6 Influence of temperature on the thermal diffusivity of PCM slurry: a) – 10% PCM, b) – 20% PCM, c) – 30% PCM

When the ambient temperature of PCM slurry increases, the thermal diffusivity of the mixture decreases up to 65ºC, but after that increases relatively quickly. Additionally, it can be observed that with increasing the concentration of PCM in the mixture, the dynamic viscosity of the PCM slurry a significant decrease.

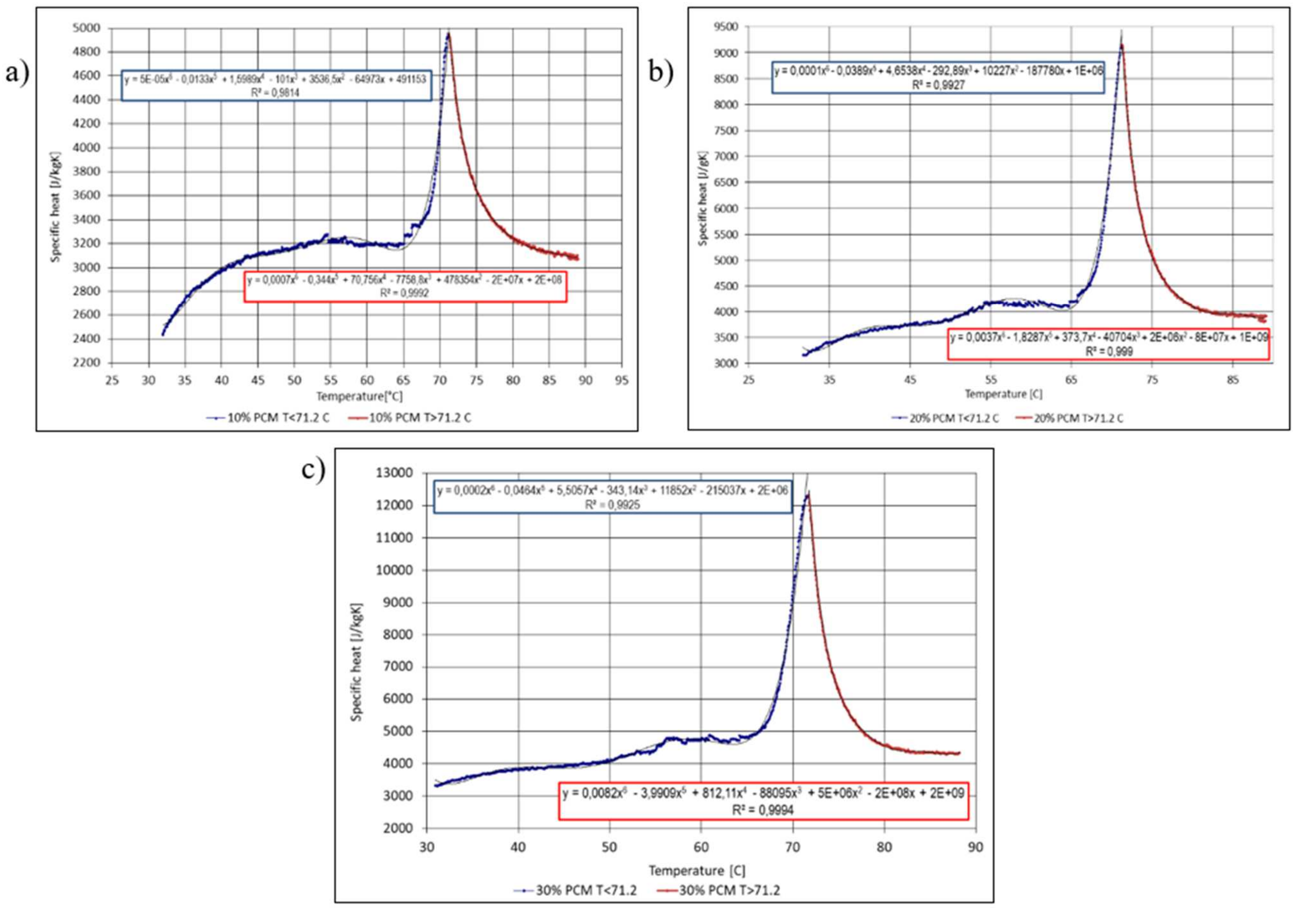

Figure 7 Influence of temperature on the specific heat of PCM slurry: a) – 10% PCM, b) – 20% PCM, c) – 30% PCM

When the ambient temperature of PCM slurry increases, the specific heat of the mixture decreases up to 73ºC, but after that decreases relatively quickly. Additionally, it can be observed that with increasing the concentration of PCM in the mixture, the specific heat of the PCM slurry a significant increase.

2.2 Numerical model

The numerical analysis encompassed medium circulation in a heating system (central heating) where the thermal energy required to acquire the necessary heat-transfer medium temperature was obtained as a result of solid fuel combustion in a heating boiler. The heated medium is supplied via pump to a double-wall plate heat exchanger, where the heat is transferred to the air flowing around the external surfaces of the heat exchanger. The cooled medium is drained to the boiler, where it is heated again, closing the circulation of the medium in the system. Figure 8 presents a diagram of the examined central heating system.

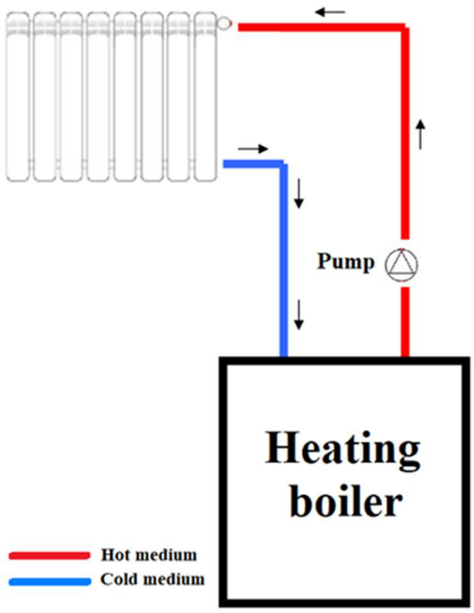

Figure 8 Analysed heating system

2.2.1 Geometry

Test subject geometry consists of a spatial model of fluid volume isolated from the developed geometry of a heat exchanger constructed from a 1.25 mm-thick steel sheet and with dimensions of 500 mm x 500 mm, which constitutes the image of a real double-wall plate heat exchanger. The distance between plates is 20 mm. Figure 9 presents the developed heat exchanger spatial model that constitutes the subject of model testing.

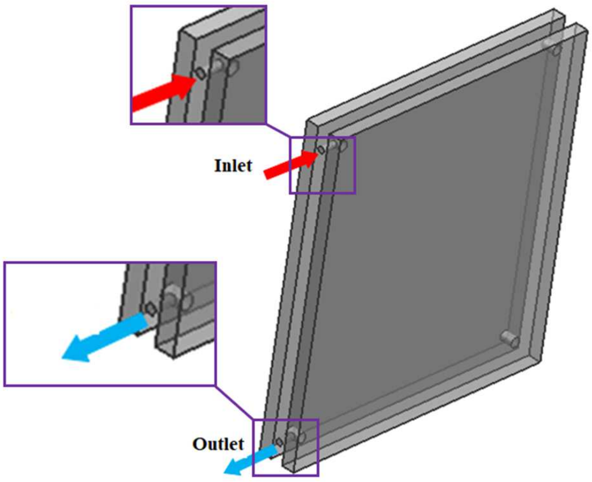

Figure 9 Double-wall heat exchanger spatial model

2.2.2 Numerical grid

The numerical solution discretisation area consists of the fluid volume isolated from the double-wall plate heat exchanger geometry, generated using 68079 simple elements mutually connected with 14578 nodes. Figure 10 presents the discretisation area of the analysed heat exchanger numerical model. The numerical grid was exported to the Ansys-Fluent program.

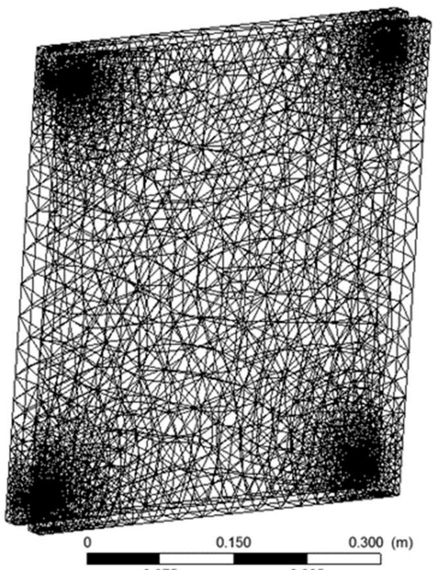

Figure 10 Heat exchanger numerical grid

2.3 Numerical model assumptions

The CFD method consists in obtaining a solution of a coupled system of differential equations defining the conservation of mass, momentum and energy principles in the following forms [1]:

- conservation of mass equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m \tag{1}$$

where:

t time, s

ρ fluid density, *kg m⁻³*
$\vec{v}$ fluid element velocity vector, *m s⁻¹*
S_m source term related to mass transfer, *kg m⁻³ s⁻¹*

- conservation of momentum equation [1]:

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla\cdot(\tilde{\tau})+\rho\vec{g}+\vec{F} \quad (2)$$

where:

$\bar{v}$ fluid element velocity vector, *m s⁻¹*
p fluid pressure, *Pa*
μ fluid dynamic viscosity, *Pa s*
$\vec{g}$ gravitational acceleration, *m s⁻²*
$\tilde{\tau}$ stress tensor, *kg m⁻³ s⁻¹*
$\vec{F}$ vector of internal forces exerted on the body in the cross-section, *N*

- conservation of energy equation [1]:

$$\frac{\partial}{\partial t}(\rho E)+\nabla(\vec{v}(\rho E+p))=\nabla\left(k_{eff}\nabla T-\sum h_j\vec{J}_j+(\tilde{\tau}_{eff}\cdot\vec{v})\right)+S_h \quad (3)$$

where:

t time, *s*
$\vec{v}$ fluid element velocity vector, *m s⁻¹*
h enthalpy, *J kg⁻¹*
T fluid temperature gradient, *K*
S_h source term related to energy transfer, *J m⁻³*
$\tilde{\tau}_{eff}$ stress tensor, *kg m⁻³ s⁻¹*
p fluid pressure, *Pa*
ρ fluid density, *kg m⁻³*
k_{eff} effective conductivity coefficient, *W m⁻¹ K⁻¹*

The influence of disturbances occurring during the heat-transfer medium transfer process as a result of energy loss due to friction against the walls has been described using a turbulence model *k*-*ε*. The solution obtainment process is based on identifying the turbulent viscosity value μ_t using the eddy kinetic energy *k* and dissipation speed *ε*. The turbulent viscosity model μ_t is described using the following equation [1]:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \quad (5)$$

where:

k velocity fluctuation (turbulent) kinetic energy, $m^2\,s^{-2}$
ε turbulent kinetic energy dissipation speed, $m^2\,s^{-3}$
μ_t eddy viscosity, *Pa s*
C_μ empirical constant, $C\mu$=0.09
ρ fluid density, *kg m⁻³*

Fluid transport equations for turbulent kinetic energy ***k*** and dissipation ***ε*** in terms of CFD methods are described using the following relationships [1]:

- for turbulent kinetic energy:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k v_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \quad (6)$$

where:

k velocity fluctuation (turbulent) kinetic energy, $m^2\,s^{-2}$
V fluid element velocity vector, *m s⁻¹*
t time, *s*
μ_t eddy viscosity, *Pa s*
σ_k turbulent Prandtl number, $\sigma_k = 1.0$
P local vorticity fluctuation production,
ε turbulent kinetic energy dissipation speed, $m^2\,s^{-3}$
ρ fluid density, *kg m⁻³*
S_k source term, *kg m⁻³ s⁻¹*

- for turbulent dissipation rate [1]:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon v_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(Gk+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \quad (7)$$

where:

k velocity fluctuation (turbulent) kinetic energy, $m^2\,s^{-2}$
$\bar{u}$ fluid element velocity vector, *m s⁻¹*
t time, *s*
μ_t eddy viscosity, *Pa s*
σ_ε turbulent Prandtl number, $\sigma_\varepsilon = 1.3$
ε turbulent kinetic energy dissipation speed, $m^2\,s^{-3}$
$C_{1\varepsilon}$ empirical constant, $C_{1\varepsilon}$=1.44
$C_{2\varepsilon}$ empirical constant, $C_{2\varepsilon}$=1.92

PCM slurry density variation value has been defined with the following relationship:

$$\frac{d\rho_{zawPCM}}{dt}=\rho_w\left(1+\frac{dX}{dt}\right) \quad (8)$$

where:

X PCM material participation in the slurry,
ϱ_{zawPCM} PCM slurry density, *kg m⁻³*
ϱ_w heat-transfer medium density, *kg m⁻³*

The following local numerical model solution uniqueness conditions were assumed:
- initial medium temperature – 300 K (26.9°C),
- medium temperature at inlet - 348 K (≈75°C),
- specific heat c_p of PCM slurry:
  - for 10% PCM – c_p= 5e⁻⁵T⁶ – 0.0133T⁵ + 1.5989T⁴ – 101T³ + 3536.5T² – 64973T + 491153 [J/kgK] for T< 71.2°C and c_p = 0.0007T⁶ - 0,344T⁵ + 70.756T⁴ – 7758.8T³ + 478354T² - 2e⁷T + 2e⁸ [J/kgK] for T ≥ 71.2°C,
  - for 20% PCM – c_p = 0.0001x⁶ - 0,0389T⁵ + 4.6538T⁴ – 292.89T³ + 10227T² – 187780T + 1e⁶ [J/kgK] for T< 71.2°C and c_p = 0.0037T⁶ – 1.8287T⁵ + 373.7T⁴ – 40704T³ + 2e⁶T² – 8e⁷T + 1e⁹ [J/kgK] for T ≥ 71.2°C,

- for 30% PCM – $c_p = 0{,}0002T^6 - 0{,}0464T^5 + 5{,}5057T^4 - 343{,}14T^3 + 11852T^2 - 215037T + 2e^6$ [J/kgK] for T< 71.2°C and $c_p = 0{,}0082T^6 - 3{,}9909T^5 + 812{,}11T^4 - 88095T^3 + 5e^6T^2 - 2e^8T + 2e^9$ [J/kgK] for T ≥ 71.2°C,

- thermal diffusivity α of PCM slurry:
  - for 10% PCM – $\alpha = 3e^{-6}x^5 - 0.0009 \cdot T^4 + 0.1132 \cdot T^3 - 7.3426 \cdot T^2 + 236.17 \cdot T - 3010.9$ [m²/s],
  - for 20% PCM - $\alpha = 2.5e^{-7} \cdot T^5 - 0.0002 \cdot T^4 + 0.0256 \cdot T^3 - 1.754 \cdot T^2 + 59.071 \cdot T - 781.62$ [m²/s],
  - for 30% PCM - $\alpha = -4e^{-6} \cdot T^5 + 0.0014 \cdot T^4 - 0.1727 \cdot T^3 + 10.939 \cdot T^2 - 343.2 \cdot T + 4268.2$ [m²/s],
- dynamic viscosity of PCM slurry:
  - for 10% PCM – $\mu = 0.0001 \cdot T + 0.0214$ [Pa·s],
  - for 20% PCM - $\mu = 0.0009 \cdot T + 0.1191$ [Pa·s],
  - for 30% PCM - $\mu = 0.003 \cdot T + 0.4368$ [Pa·s],
- volumetric fluid flow rate – 1.2 [m³/h],
- specific heat c_p of water - 4182 [J/kg K],
- thermal conductivity of water - 0.6 [W/mK],
- dynamic viscosity of water - 0.001003 [Pa·s],

The following global settings were considered in the Ansys-Fluent program:
- pressure - 10 [bar],
- convective heat-transfer coefficient for air - 10 [W/m²K],
- time scale - 3600 seconds.

3 Result

Figure 11 presents the heat-transfer medium temperature variation distribution (water and PCM slurry) by measuring the value of the investigated parameter at the model heat exchanger outlet.

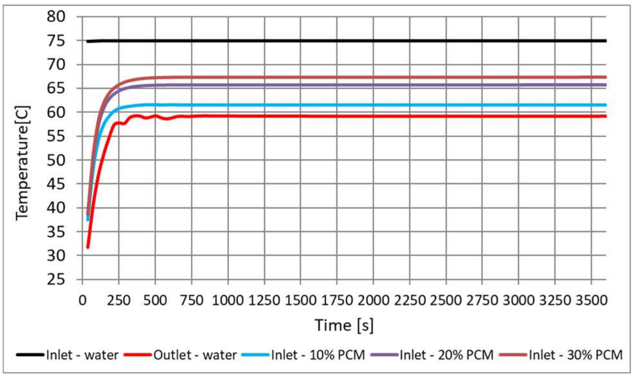

Figure 11 Changes of temperature at the outlet of heat exchanger depending on PCM concentration in the heat-transfer medium

The conducted model test results show that the obtained water temperature value at the outlet was 59.14°C. For a 10% PCM solution, the registered temperature value was at a level of 61.51°C, whereas the medium temperature for a 20% PCM water solution was 65.72°C, and 67.36°C for a 30% PCM concentration. The investigated parameter values, which constitute a numerical model solution of the PCM slurry transfer process in a model heat exchanger, have been compiled in Table 1.

Table 1 The temperature variation values (water and PCM slurry) in time interval of 3600 seconds

No.	Time [s]	Outlet - water Temperature [°C]	Outlet - 10% PCM Temperature [°C]	Outlet - 20% PCM Temperature [°C]	Outlet - 30% PCM Temperature [°C]
1	36	31.79	37.43	38.55	38.77
2	72	40.42	47.9	50.06	50.84
3	108	46.73	54.04	57.1	58.11
4	144	51.06	57.29	60.75	61.88
5	180	54.47	59.06	62.69	63.89
6	216	57.32	60.19	63.82	65.08
7	252	57.74	60.79	64.51	65.83
8	288	57.64	61.07	64.94	66.32
9	324	58.85	61.21	65.22	66.66
10	360	59.23	61.38	65.39	66.89
11	396	59.17	61.47	65.51	67.04
12	432	58.78	61.54	65.58	67.15
13	468	58.97	61.54	65.63	67.22
14	504	59.21	61.53	65.67	67.27
15	540	58.82	61.52	65.69	67.3
16	576	58.59	61.52	65.7	67.32

17	612	58.78	61.53	65.71	67.33
18	648	59.08	61.52	65.72	67.34
19	684	59.14	61.52	65.72	67.35
20	720	59.09	61.52	65.72	67.35
21	756	59.14	61.51	65.72	67.36
22	792	59.19	61.51	65.72	67.36
23	828	59.21	61.51	65.72	67.36
24	864	59.22	61.51	65.72	67.36
25	900	59.21	61.51	65.72	67.36
26	936	59.19	61.51	65.72	67.36
27	972	59.18	61.51	65.72	67.36
28	1008	59.19	61.51	65.72	67.36
29	1044	59.19	61.51	65.72	67.36
30	1080	59.17	61.51	65.72	67.36
31	1116	59.16	61.51	65.72	67.36
32	1152	59.17	61.51	65.72	67.36
33	1188	59.17	61.51	65.72	67.36
34	1224	59.16	61.51	65.72	67.36
35	1260	59.16	61.51	65.72	67.36
36	1296	59.16	61.51	65.72	67.36
37	1332	59.16	61.51	65.72	67.36
38	1368	59.15	61.51	65.72	67.36
39	1404	59.15	61.51	65.72	67.36
40	1440	59.16	61.51	65.72	67.36
41	1476	59.15	61.51	65.72	67.36
42	1512	59.15	61.51	65.72	67.36
43	1548	59.15	61.51	65.72	67.36
44	1584	59.14	61.51	65.73	67.36
45	1620	59.14	61.51	65.73	67.36
46	1656	59.14	61.51	65.73	67.36
47	1692	59.14	61.51	65.73	67.36
48	1728	59.14	61.51	65.73	67.36
49	1764	59.14	61.51	65.73	67.36
50	1800	59.14	61.51	65.73	67.36
51	1836	59.14	61.51	65.73	67.36
52	1872	59.14	61.51	65.73	67.36
53	1908	59.14	61.51	65.73	67.36
54	1944	59.14	61.51	65.73	67.36
55	1980	59.14	61.51	65.73	67.36
56	2016	59.14	61.51	65.73	67.36
57	2052	59.14	61.51	65.73	67.36
58	2088	59.14	61.51	65.73	67.36
…	……	……	……	……	……
100	3600	59.15	61.51	65.73	67.36

Additionally, figures 12-15 present the thermal field variation distributions on the heat exchanger surface, where the utilised heat-transfer media were water (Figure 12) and slurries constituting 10% (Figure 13), 20% (Figure 14) and 30% (Figure 15) PCM dispersions.

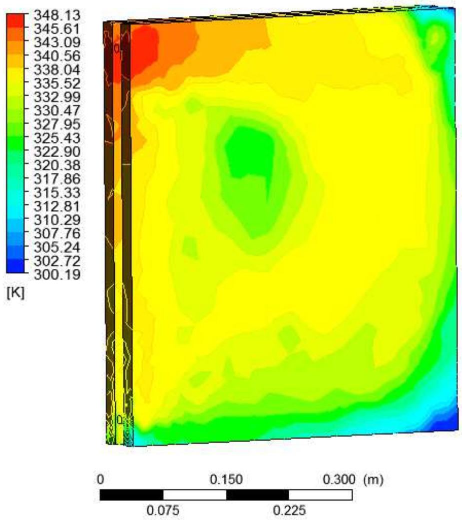

Figure 12 Water heat-transfer medium thermal field variation distribution after 3600 seconds

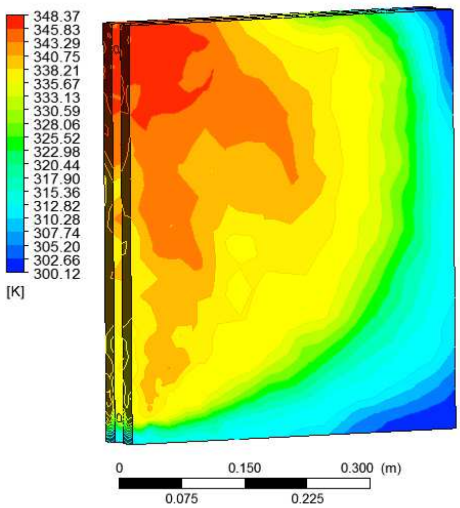

Figure 13 10% PCM slurry thermal field variation distribution after 3600 seconds

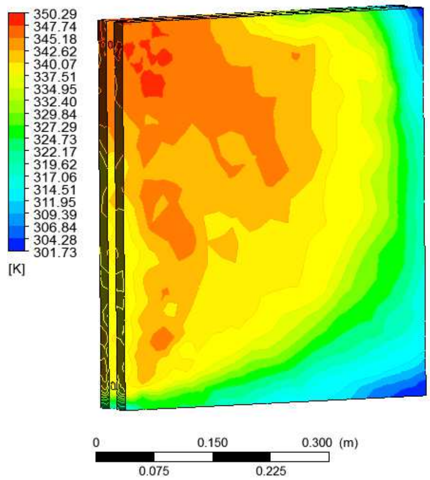

Figure 14 20% PCM slurry thermal field variation distribution after 3600 seconds

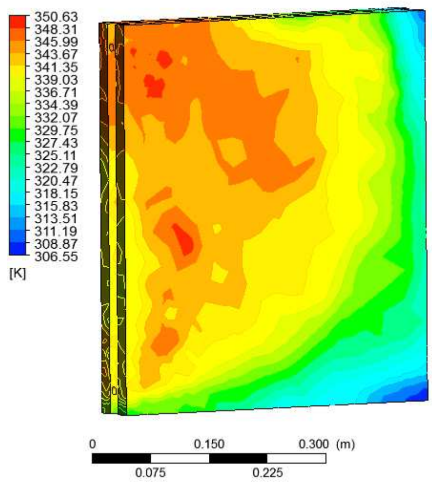

Figure 15 30% PCM slurry thermal field variation distribution after 3600 seconds

4 Conclusion

Laboratory tests of water slurries with PCM participation were conducted

with the intent to determine the variations of selected physical parameters such as viscosity, thermal diffusion and specific heat. The obtained parameter values that characterise PCM slurry properties were compared with the parameter values of water utilised as a standard heat-transfer medium in heating systems. The determined PCM slurry physical parameters constituted input data for a numerical model. A numerical model of a heat exchanger in the form of a steel double-wall plate heater was developed as the test subject of the analysed heating system with the use of CFD methods.

Based on the results of the conducted model tests, the following conclusions were formulated:

- the obtained model test results confirm the possibility to utilise PCM slurry as a heat-transfer medium,
- the developed numerical model results need to be applied to a real heating system utilising PCM slurry as a heat-transfer medium,
- according to the performed numerical analysis, a heat-transfer medium in the form of a slurry with a 30% PCM addition exhibits the best properties.

Acknowledgement
The work was carried out as part of statutory research no. 14310016-144 conducted at the Central Mining Institute in Katowice, financed by the Ministry of Science and Higher Education, Poland.

References

[1] ANSYS FLUENT 12.0 Release Notes, ANSYS, Inc. 2009-03-02.
[2] CABEZA, L.F., CASTELL, A., BARRENECHE, C., DE GRACIA, A., FERNÁNDEZ, A.I.: Materials used as PCM in thermal energy storage in buildings: a review, *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 3, pp. 1675-1695, 2011.
[3] ESEN, M., AYHAN, T.: Development of a model compatible with solar assisted cylindrical energy storage tank and variation of stored energy with time for different phase change materials, *Energy Conversion Management*, Vol. 37, No. 12, pp. 1775-1785, 1996.
[4] HORNAK, P., KOTTFER, D., KACZMAREK, L., KIANICOVA, M., BALKO, J., REHAK, F., PEKARCIKOVA, M., CIZNAR, P.: The effect of pressure, bias voltage and annealing temperature on N-2 and N-2 + SiH4 doped WC/C DC magnetron sputtered layers, *Ceramics-Silikaty*, Vol. 62, No. 1, pp. 97-107, 2018.
[5] JANKOWSKI, N.R., MCCLUSKEY, F.P.: A review of phase change materials for vehicle component thermal buffering, *Applied Energy*, Vol. 113, No. January, pp. 1525-1561, 2014.
[6] JURKOWSKA, M., SZCZYGIEŁ, I.: Review on properties of microencapsulated phase change materials slurries (mPCMS), *Applied Thermal Engineering*, Vol. 98, No. April, pp. 365-373, 2016.
[7] MANFRIDA, G., SECCHI, R., STAŃCZYK, K.: Modelling and simulation of phase change material latent heat storages applied to a solar-powered Organic Rankine Cycle, *Applied Energy*, Vol. 179, No. October, pp. 378-388, 2016.
[8] STEJSKAL, T., SVETLÍK, J., DEMEČ, P., ZILINSKY, A., KOVAC, J.: Prospective increase in the heat pump's efficiency through arrangement in a three-temperature system, *Advances in Mechanical Engineering*, Vol. 11, No. 10, pp. 1-13, 2019.
[9] TREBUNA, P., KLIMENT, M., EDL, M., PETRIK, M.: *Creation of simulation model of expansion of production in manufacturing companies*, Modelling of Mechanical and Mechatronic Systems 2014 (MMaMS), Book Series: Procedia Engineering, Vol. 96, pp. 477-482, 2014.
[10] PEKARCIKOVA, M., TREBUNA, P., MARKOVIC, J.: *Case study of modelling the logistics chain in production*, Modelling of Mechanical and Mechatronic Systems 2014 (MMaMS), Book Series: Procedia Engineering, Vol. 96, pp. 355-361, 2014.
[11] KLIMENT, M., POPOVIC, R., JANEK, J.: *Analysis of the production process in the selected company and proposal a possible model optimization through PLM software module Tecnomatix Plant Simualtion*, Modelling of Mechanical and Mechatronic Systems 2014 (MMaMS), Book Series: Procedia Engineering, Vol. 96, pp. 221-226, 2014.
[12] MEHLING, H., CABEZA, L.F.: *Heat and cold storage with PCM*, An up to date introduction into basics and applications, Springer, 2008.
[13] NETZSCH, Proven Excellence, [online], Available: https://www.netzsch.com/en/ [25. Feb. 2020], 2020.
[14] AZO Nano, [online], Available: https://www.azonano.com/equipment-details.aspx?EquipID=302 [25. Feb. 2020], 2020.
[15] TA Instruments, Rheometers, [online], Available: http://www.tainstruments.com/pdf/brochure/2005_Rheology_Brochure.pdf [25. Feb. 2020], 2006.
[16] REGIN, A.F., SOLANKI, S.C., SAINI, J.S.: An analysis of a packed bed latent heat thermal energy storage system using PCM capsules: numerical investigation, Renewable Energy, Vol. 34, No. 7, pp. 1765-1773, 2009.
[17] STÜCKLE, A.: *Modelling of high temperature storage systems for latent heat*, Proceedings 7th Modelica Conference, Como, Italy, Sep. 20-22, 2009.
[18] ZALBA, B., MARÌN, J.M., CABEZA, L.F., MEHLING, H.: Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering*, Vol. 23, No. 3, pp. 251-283, 2003.
[19] WEI, J., KAWAGUCHI, Y., HIRANO, S., TAKEUCHI, H.: Study on a PCM heat storage system for rapid heat supply, *Applied Thermal Engineering*, Vol. 25, No. 5, pp.2903-2920, 2005.
[20] ZHANG, Y., ZHOU, G., LIN, K., ZHANG, Q., DI, H.: Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook, *Building and Environment*, Vol. 42, No. 6, pp. 2197-2209, 2007.
[21] ZHANG, X.-X, TAO, X.-M., YICK, K.-L, WANG, X.-C.: Structure and thermal stability of microencapsulated phase-change materials, *Colloid Polymer Science*, Vol. 282, No. 4, pp. 330-336, 2004.

Review process
Single-blind peer review process.