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THERMAL STORAGE AS A WAY TO ATTENUATE FLUID-TEMPERATURE FLUCTUATIONS: SENSIBLE-HEAT VERSUS LATENT-HEAT STORAGE MATERIALS

SHRANJEVANJE TOPLOTE KOT POT ZA ZMANJŠANJE NIHANJA TEMPERATURE: OBČUTLJIVI MATERIALI PROTI MATERIALOM ZA SHRANJEVANJE LATENTNE TOPLOTE

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A stable fluid temperature is quite important in many technical applications and thermal storage is one of the ways to attenuate fluid-temperature fluctuations. Both sensible- and latent-heat storage materials can be used for this purpose. A theoretical study comprising numerical simulations was conducted in order to investigate the behaviors of sensible- and latent-heat storage for attenuating fluid-temperature fluctuations. The studied case was a circular channel, through which a fluid passed, surrounded by a thermal-storage material. Two sensible-heat storage materials (copper and concrete) and two latent-heat storage materials (n-octadecane and calcium chloride hexahydrate) were considered in the performed study. Water was the fluid in all the studied cases. The main goal of the investigations was to assess the thermal response of each variant under the same conditions. The length of the channel, the flow rate of water and the volume of the heat-storage material were the same in all the variants.

Keywords: temperature stability, thermal storage, phase-change materials

Stabilna temperatura tekočine je pomembna na mnogih tehničnih področjih uporabe, shranjevanje toplote pa je ena od poti za zmanjšanje nihanja temperature. Za ta namen je mogoče uporabiti občutljive materiale in materiale za shranjevanje latentne toplote. Izvršena je bila teoretična študija, ki je obsegala numerično simulacijo, z namenom preučitve vedenja občutljivih materialov in materialov za shranjevanje latentne toplote za zmanjšanje nihanja temperature tekočine. Preučevan primer je bil okrogel kanal, skozi katerega je tekla tekočina, obdan z materialom za shranjevanje toplote. V študiji sta bila obravnavana dva občutljiva materiala za shranjevanje toplote (baker in beton) in dva materiala za shranjevanje toplote (n-oktadekan ter kalcijev klorid heksahidrat). V vseh preučevanih primerih je bila tekočina voda. Glavni namen študije je bil ugotoviti toplotni odgovor v enakih razmerah za vsako varianto.

Ključne besede: stabilnost temperature, shranjevanje toplote, materiali s faznimi premenami

1 INTRODUCTION

A constant fluid temperature plays an important role in many applications from laboratory experiments to the extracorporeal blood circulation. Some deviations from the desired fluid temperature can occur due to a number of reasons such as an imperfect temperature control or a fluctuating heat load. Temperature fluctuations can be either stochastic or they can follow a certain pattern (e.g., depending on the dead band of a temperature controller). Thermal storage with both sensible- and latent-heat storage materials can be employed to attenuate fluid-temperature fluctuations. The behavior of a sensible-heat storage used for this purpose is rather independent of the fluid temperature (the same material can be used to attenuate the fluid-temperature fluctuations at various temperatures). Another advantage of sensible-heat storage is a rather good thermal conductivity of many sensible-heat storage materials, metals in particular. Latent-heat storage materials (phase-change materials – PCMs) provide a high thermal-storage capacity in a narrow temperature interval around the phase-change temperature. If a PCM is used for attenuating fluid-temperature fluctuations, it needs to be chosen with regard to the fluid temperature in order to make use of that high thermal capacity (a fluid temperature needs to fluctuate within the melting range of a material). A schematic presentation of an application of heat storage for attenuating fluid-temperature fluctuations is shown in **Figure 1**. There are harmonic oscillations of the fluid temperature at the inlet of the attenuator because that was the case in the numerical investigations presented in this paper.

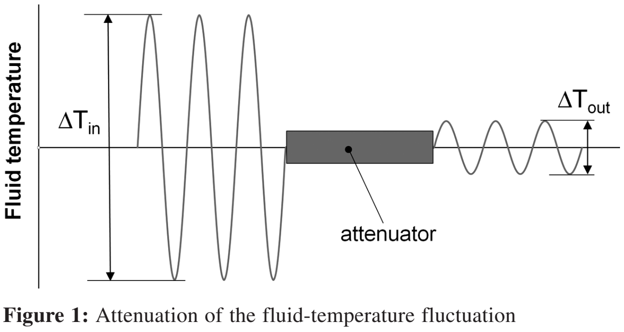

Figure 1: Attenuation of the fluid-temperature fluctuation
Slika 1: Zadrževanje nihanja temperature tekočine

Some studies into the attenuation of temperature gradients or temperature instabilities have been published in the last decade. Lawton et al.[1] reported theoretical analyses and experimental observations of the thermal performance of direct-contact packed-bed thermal-gradient attenuators. The packed bed in this case was a cylindrical canister filled with spheres. The authors presented the attenuator transfer functions for various parameters such as the diameter of the canister, the diameter of the spheres, the number of the spheres and the fluid-flow rate. The attenuator in the form of a 100 mm diameter plastic canister containing 10000 steel spheres with the diameter of 6.4 mm reduced the harmonic variations of the water temperature with the peak-to-peak amplitude of 150 mK at the input to the variations of just 0.6 mK at the output. Alawadhi[2] presented a numerical study evaluating the thermal performance of a fluid-temperature regulation unit. The unit was a two-dimensional channel with a phase-change material on each side. The author numerically investigated the thermal characteristics of the unit for a step function change and a periodic change of the inlet temperature.

2 PROBLEM DESCRIPTION

The idea behind the use of thermal storage for attenuating fluid-temperature fluctuations is the increase in the thermal inertia of the system. A thermal-storage material, in this case, behaves as both the heat sink and the heat source. When the fluid temperature is higher than the temperature of the heat-storage material, the heat flows from the fluid to the thermal-storage material. Similarly, when the fluid temperature is lower than that of the heat-storage material, the heat flows in the opposite direction. Since the overall thermal-storage capacity of such a thermal mass is limited, there are some constraints for the attenuation characteristics of this approach in terms of the amplitudes and frequencies of the temperature fluctuations. **Figure 2** shows one period of the square-wave, sine-wave and triangle-wave temperature changes with the same amplitude and the same frequency. If the temperature of the fluid at the inlet of the attenuator followed one of the waveforms, the heat would flow from the fluid to the thermal-storage material during the first half of the period and it would flow from the heat storage material to the fluid during the second half of the period. The mean value of the heat flux for the whole period (or any number of periods) would be zero and the mean fluid temperatures at the inlet and the outlet of the attenuator would be the same. The amplitude of the fluid-temperature fluctuations at the outlet of the attenuator depends on many parameters, mostly related to heat transfer – the attenuator is a kind of a heat exchanger in this case. If the attenuator only contains sensible-heat storage material, its attenuation characteristic will be almost independent of the mean fluid temperature at the inlet since the thermophysical properties such as the thermal conductivity and heat capacity do not significantly change with the temperature (in the range of ± 20 K). The situation changes considerably when latent-heat storage is used. PCMs provide a large thermal-storage capacity in their melting ranges but their thermal-storage capacity is much smaller outside the melting range. This paper reports on the numerical investigations of a thermal response of an attenuator of fluid-temperature fluctuations containing sensible- and latent-heat storage materials under various conditions.

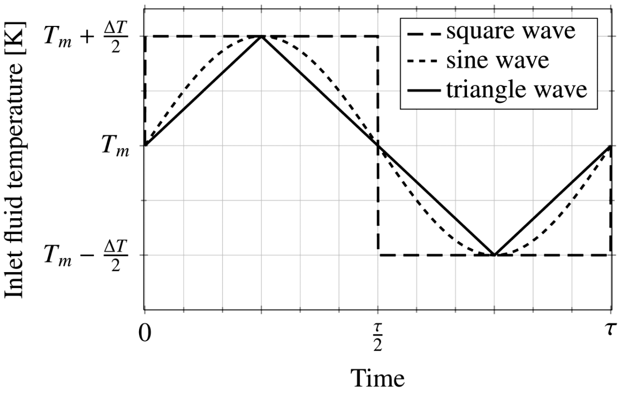

Figure 2: Inlet temperature oscillations (waveforms)
Slika 2: Spreminjanje vstopne temperature (v obliki valov)

3 CASE STUDY

The studied attenuator of the fluid-temperature fluctuation was a circular tube, through which the fluid flowed, surrounded by a thermal-storage material. Water was the fluid in all the studied cases. Two sensible-heat storage materials and two latent-heat storage materials were considered in the study. The schematic view of the attenuator is in **Figure 3**. The main goal of the investigations was to assess the thermal response of each variant under the same conditions. For this reason the same dimensions of the attenuator as well as the same water flow rate were considered in all the studied cases. The length of the attenuator was 10 m. In practice, an attenuator can be built of shorter modules arranged in the meander-flow fashion. The internal diameter of the tube was 25 mm and the thickness of the annular layer of the heat-storage material surrounding the tube was 25 mm (the volume of the heat-storage material was about 60 L). A suitable geometry of the attenuator for specific conditions can be obtained through a multi-parameter

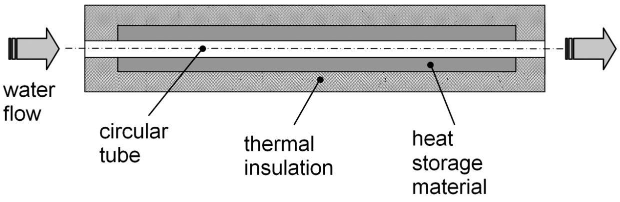

Figure 3: Thermal-storage attenuator
Slika 3: Zadrževalnik za shranjevanje toplote

optimization.[3] The thermal insulation on the external side of the heat-storage material was replaced with an adiabatic boundary condition in the numerical model. This simplification was justified with a rather small difference between the fluid temperature and the ambient air temperature.

A number of papers dealing with thermal-storage materials, techniques and related phenomena have been published in the last couple of years.[4–6] There is a variety of both sensible- and latent-heat storage materials that can be used in the devices for attenuating fluid-temperature fluctuations. Copper was chosen as one of the sensible-heat storage materials in this numerical study because of its very good thermal conductivity. The other sensible-heat storage material was concrete. Concrete is a very common and inexpensive material that can be used for many purposes. The alkanes (paraffins) with the formula C_nH_{n+2} are probably the most common category of organic phase-change materials. The melting temperature of an alkane depends on the number of carbon atoms. That makes alkanes usable in many thermal-storage applications (both in heat and cold storage). For example, nonane (C_9H_{20}) has a melting temperature of –53 °C, while dotetracontane ($C_{42}H_{86}$) has a melting temperature of 86 °C. N-octadecane ($C_{18}H_{38}$) that has a rather high latent heat of fusion was chosen to represent organic PCMs in this study. As for the inorganic PCMs, calcium chloride hexahydrate ($CaCl_2\cdot 6H_2O$) was selected as it is one of the most common salts that can be used as a PCM. Tyagi and Buddhi[7] carried out a thermal cycle test of calcium chloride hexahydrate with the aim to assess the stability of its thermophysical properties with a number of melting cycles. They found a little change in the properties even after 1000 melting-solidification cycles. The stability of its thermophysical properties was another reason for including $CaCl_2\cdot 6H_2O$ in the numerical study of the fluid-temperature attenuation. Some of the properties of the heat-storage materials chosen for this study are in **Table 1**. It should be pointed out that the thermophysical properties of the considered materials (especially of the PCMs) vary in various literature sources.

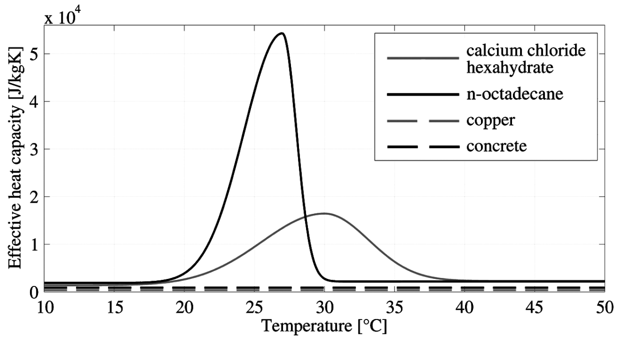

Figure 4: Effective-heat capacities
Slika 4: Efektivna toplotna kapaciteta

Table 1: Material properties
Tabela 1: Lastnosti materiala

	copper	concrete	n-octadecane	calcium chloride hexahydrate
ρ/(kg/m^3)	8940	2200	780	1400
c/(kJ/(kg K))	0.385	0.88	2.89	1.4 (s) 2.1 (l)
k/(W/(m K))	401	1.4	0.16	1
Latent heat (kJ kg^{-1})	n. a.	n. a.	244	140

4 NUMERICAL MODEL

The numerical model of the attenuator was created in MATLAB with using the control-volume method. The model consisted of two parts (sub-models). The first sub-model addressed the fluid flow in the tube and the convective heat transfer associated with it. The second sub-model dealt with the heat transfer inside the heat-storage material. The governing equation for the heat and mass transfers in the fluid flow expressed in the cylindrical coordinate system has the following form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k_\mathrm{f}\, r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k_\mathrm{f}\, r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k_\mathrm{f}\, r\frac{\partial T}{\partial z}\right)+ \\ +w\rho_\mathrm{f}\, c_\mathrm{f}\,\frac{\partial T}{\partial t}=\rho_\mathrm{f}\, c_\mathrm{f}\,\frac{\partial T}{\partial t} \tag{1}$$

where r, φ and z are the coordinates, w/(m/s) is the fluid velocity, ρ_f/(kg/m^3) is the fluid density and c_f/(J/(kg K)) is the fluid thermal capacity. The governing equation for the heat transfer in the heat-storage material is rather similar:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(kr\frac{\partial T}{\partial z}\right)=\rho c_\mathrm{eff}\,\frac{\partial T}{\partial t} \tag{2}$$

Considering the rotational symmetry of the attenuator, the studied problem is reduced to a 2D model with only the radial r and longitudinal z coordinates. The circumferential coordinate φ is not taken into account assuming that the heat flux in the circumferential coordinate equals zero. As can be seen in equation (2) an effective heat-capacity method[8] was adopted to address the phase change of the latent-heat storage materials. The effective heat capacities of the four materials involved in the numerical study are shown in **Figure 4**.

The value of the heat-transfer coefficient for the convective heat transfer between the fluid and the inner surface of the tube was determined according to the convective heat-transfer correlations:[9]

$$Nu=\frac{\frac{Nu}{\mathrm{Re}}(\mathrm{Re}-1000)\,\mathrm{Pr}^{2/3}}{1+12.7\left(\frac{Nu}{\mathrm{Re}\,\mathrm{Pr}^{1/3}}\right)^{1/2}(\mathrm{Pr}^{2/3}-1)} \tag{3}$$

The correlation expressed with equation (3) is valid for the Reynolds number in the range of $3000 < Re < 5 \times 10^5$

and for the Prandtl number in the range of $0.5 < Pr < 2000$. Both conditions were satisfied for the investigated conditions. Heat-transfer coefficient h was then obtained from the definition of the Nusselt number:

$$Nu = h(D/k_f) \tag{4}$$

where D/m is the diameter of the tube and k_f/(W/(m K)) is the thermal conductivity of the fluid. The value of the heat-transfer coefficient was h = 1000 W/(m^2 K) in the investigated cases.

5 RESULTS AND DISCUSSION

All the numerical simulations were carried out for the water-mass flow rate of 0.1 kg/s (360 kg/h) and the harmonic oscillations of the inlet water temperature (the sine wave). As can be seen in **Figure 2**, the waveforms differ in the amount of heat carried in the temperature fluctuations. This amount of heat is proportional to the area of the wave. For the same frequency (period) and amplitude of the waves, it is the largest for the square wave and the smallest for the triangle wave.

The first set of numerical experiments addressed the peak-to-peak amplitudes. Two peak-to-peak amplitudes of the water temperature variations at the inlet of the attenuator, ΔT_{in} = 10 K and ΔT_{in} = 2 K, were investigated. The wave period was 60 s. The mean value of the water temperature at the inlet of the attenuator was 30 °C in the case of copper, concrete and calcium chloride hexahydrate. The mean value of the inlet water temperature in the case of n-octadecane was 27 °C. The mean values of the inlet water temperature for the PCMs were chosen at the peaks of their effective heat capacities (**Figure 4**). Additional cases with the mean value of the water inlet temperature of 10 °C were investigated. At this temperature both PCMs are in the solid state, behaving as sensible-heat storage materials. The results of the simulations are shown in **Table 2**.

Table 2: Simulation results
Tabela 2: Rezultati simulacije

	copper	concrete	octadecane	calcium chloride hexahydrate
inlet peak-to-peak temperature amplitude	outlet peak-to-peak temperature amplitude ΔT_{out} /K			
ΔT_{in} = 10 K	1.167	3.153	0.187	0.231
ΔT_{in} = 2 K	0.231	0.627	0.039	0.044
ΔT_{in} = 10 K (solid PCMs)	n. a.	n. a.	2.569	1.563
ΔT_{in} = 2 K (solid PCMs)	n. a.	n. a.	0.510	0.309

Consequently, the influence of the temperature-change frequency (period) was numerically investigated. Simulations were done for the inlet peak-to-peak temperature amplitude of 10 K. As can be seen in **Figure 5**, the attenuation improves with the increasing frequency (shorter periods). With the shortening period of the wave less heat needs to be exchanged between the fluid and the heat-storage material and, as a result, the outlet temperature amplitude decreases.

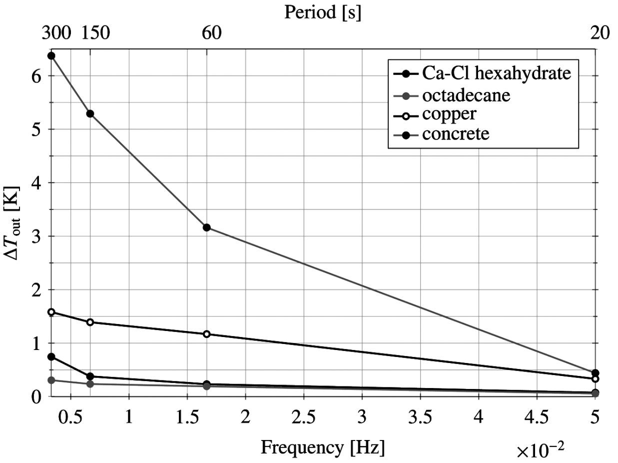

Figure 5: Influence of the wave frequency (period)
Slika 5: Vpliv frekvence vala (dolžina trajanja)

The last set of numerical investigations focused on the offset of the sine wave – the differential between the mean inlet fluid temperature and the peak of the effective heat capacity of the PCMs. Since the effective-capacity curves of the PCMs are not symmetrical, both positive and negative offsets were investigated. The results of this scenario are presented in **Figure 6**. The peak-to-peak amplitude was 10 K in this case and the period of the sine wave was 60 s. The sensible-heat storage materials (copper and concrete) have the same specific heat in the investigated temperature interval; therefore, the value of the mean inlet fluid temperature had no effect on the attenuation characteristic.

The results of all the studied cases show that the attenuation effect was the strongest in the case of n-octadecane when the inlet water temperature oscillated around the peak of its effective capacity. The attenuation effect

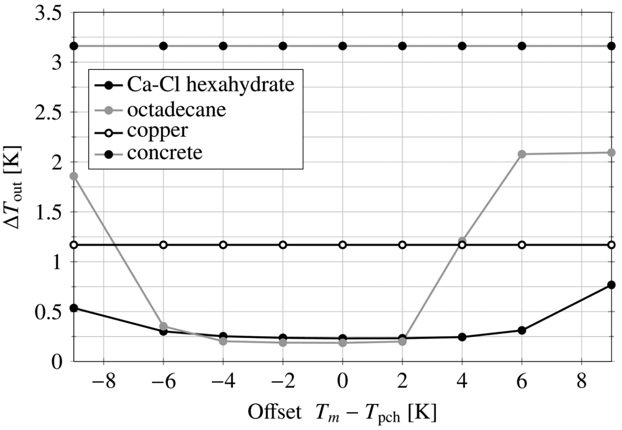

Figure 6: Influence of an offset
Slika 6: Vpliv odmika

of n-octadecane decreased with the increasing offset of the sine-wave temperature fluctuations. The same applies to calcium chloride hexahydrate. For large offsets, when the mean inlet temperature gets outside the PCM melting range, the PCM starts to behave as a sensible-heat storage material. Copper had a stronger attenuation effect on the fluid-temperature oscillations than the PCMs in the solid or liquid state.

6 CONCLUSION

The numerical investigations of the attenuation of water temperature fluctuations by means of a heat-storage-based attenuator were carried out. A numerical model of the attenuator created in MATLAB using the control-volume method was employed in the investigations. Two sensible-heat storage materials (copper and concrete) and two latent-heat storage materials (n-octadecane and calcium chloride hexahydrate) were considered in this study. The results showed that the effective heat capacity of a thermal-storage material played a more important role than its thermal conductivity in the studied scenarios. The latent-heat storage materials (PCMs) were more effective in dampening the water temperature oscillations than the sensible-heat storage materials when the water temperature oscillated around the peak values of their effective heat capacities (the water temperature oscillating in the melting range of the PCMs). The attenuation properties of the PCMs decreased very significantly when the PCMs were only in the solid or liquid state.

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