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Regular Article

Entropy generation for spiral heat exchanger with considering NEPCM charging process using hybrid nanomaterial

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Abstract In current unsteady simulation, charging of paraffin in an enclosure which is equipped with spiral pipe was scrutinized. Not only in paraffin but also in water inside the pipe, nanoparticles were dispersed to boost the thermal treatment. Outputs were reported in various stages in forms of irreversibility components. Increasing inlet velocity leads to higher liquid fraction which means better performance. As time increases, inlet velocity has lower effect on melting process. Increasing pumping power is beneficial only when time is lower than 20 min. Frictional irreversibility increases with time at initial time, and then, it reduces.

1 Introduction

Improving TES (thermal energy storage) can give us the opportunity to respond energy requests. This can grow the effectiveness of various energy technologies including solar thermal system. Environmental influence, fossil fuel resources and restricted energy supplies are the main problems that researchers are faced. Because of intermittent availability, high price of installation and maintenance, sustainable sources like wind and solar energy are required. Thermal energy storage can be an appropriate alternative solution for correcting the intermittency, and they are more efficient which can progress the wider application of the aforesaid sources [1–5]. One of the most frequently challenges with PCMs utilized in the applications of thermal energy storage is low thermal conductivity. This can pose to an imperfect discharging and charging procedures. Nanotechnology helps the researcher to solve this fault [6–19]. The efficiency of such systems is restricted in different temperatures through PCM, causing system overheating and substance failure. Phase change material is very practical in such engineering applications as water heating, electronic cooling, building heating, dry technology, air conditioning and solar energy systems [20–25]. Li et al. [26] scrutinized the transient discharging phenomena with help of nanomaterial. Sheikholeslami

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and Mahian [27] examined the impact of MHD on solidification in the presence of inorganic nanomaterial.

Numerically, the impact of HTF in a TES was analyzed by Agyenim et al. [28] who studied various configurations. Based on their results, the axial heat transfer can be ignored. Classic numerical approaches help scientist to simulate behavior of system before design step [29–55]. In addition, molecular modeling can show the nanomaterial behavior with more details [56,57]. PCM-LHTES systems involving simple pipe, circular finned pipe and pinned tube were simulated by Tay et al. [58] who found that the most efficient design with shorter phase change time in solidification procedure was related to circular finned tube. Numerically, the melting of RT82 by mixing various concentrations of Al_2O_3 in a cavity with one hot wall was reported by Arasu and Mujumdar [59]. Utilization of two forms of tree formed fins has been simulated by Sciacovelli et al. [60] for optimizing and reaching the maximum efficiency for LHTES system. As a result, there are various published scientific works expressing the importance of shape of fin in order to augment the performance of units. Numerically, the solidification procedure in a horizontal cylinder with PCM was studied by Ismail et al. [61] who found that the time of PCM solidification plummeted when the inlet fluid temperature decreased. To reduce cost of experimental procedure, various numerical approaches were suggested [62–79]. The charging treatment of PCM has been illustrated by Xiaohu et al. [80] who conducted the tests at 0°, 30°, 60° and 90° inclination. In comparison with the case at 90°, the melting duration decreased by 12.28% at 0°, 22.81% at 30° and 34.21% at 60°. The impact of inlet mass stream rate and water temperature on heat storage and thermal efficiency in a tube was investigated by Tao and He [81]. Based on their results, raising the HTF mass stream and temperature increases the rate of melting. Additionally, raising the number of tubes augments the efficiency of the heat exchanger.

In current modeling, charging of paraffin within a square enclosure was simulated. Spiral pipe was used in which hot fluid flows and converts the solid PCM to liquid. To augment PCM's thermal conductivity within charging procedure, nanopowders have been dispersed. Nanoparticles were utilized in both hot water and paraffin. FVM was selected to simulate, and outputs were demonstrated in various stages.

2 Enclosure with spiral pipe

As depicted in Fig. 1, to charge the paraffin inside a square tank, a spiral pipe was employed. Water with impose of nanoparticles was considered as testing fluid inside the spiral pipe. The reason of selecting paraffin is its high capacity to store energy and to improve its thermal feature; CuO was added in it as utilized in Ref. [82]. To model this problem, we use the below equations:

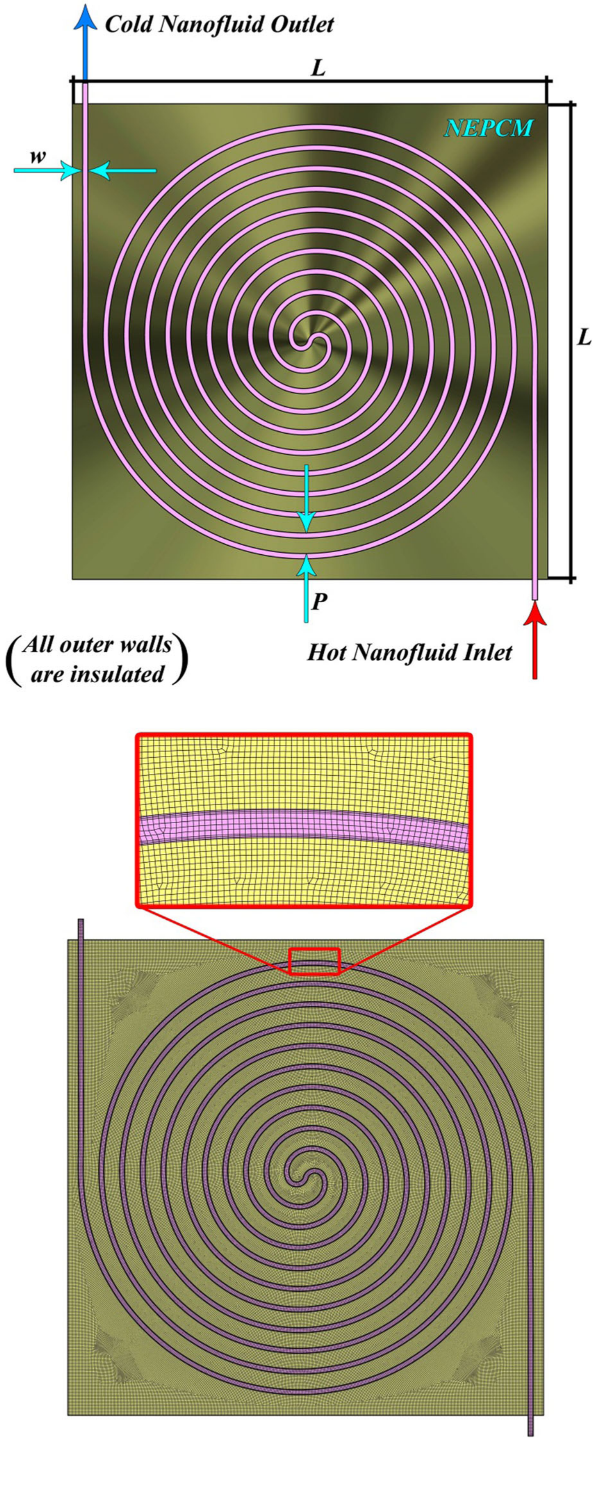
$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + \vec{V} \cdot \nabla u = \frac{1}{\rho_{nf}}(-\nabla P + \mu_{nf} \nabla^2 u) + C\, u\, \frac{(1-\lambda)^2}{\lambda^3 + \varepsilon}, \quad C = 10^5,\ \varepsilon = 10^{-3} \tag{2}$$

$$\frac{\partial v}{\partial t} + \vec{V} \cdot \nabla v = \frac{1}{\rho_{nf}}(-\nabla P + \mu_{nf} \nabla^2 v) + C\, v\, \frac{(1-\lambda)^2}{\lambda^3 + \varepsilon} + g(T - T_{ref})(\rho\beta)_{nf} \tag{3}$$

$$\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T = -\frac{\partial(\rho L \lambda)_{nf}}{\partial t} + \frac{k_{nf}}{(\rho C_p)_{nf}} \nabla^2 T \tag{4}$$

Fig. 1 Spiral unit and mesh



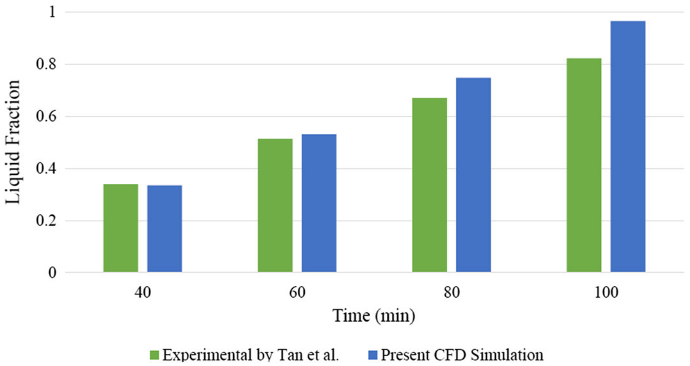


Fig. 2 Comparison of outputs with Ref. [28]

The last term of Eq. (3) appears with use of Boussinesq approximation. To include the impact of nanoparticles, homogeneous model was used as mentioned in [82] and also for hot fluid section, we utilized hybrid nanoparticles. For mixture of water with hybrid nanopowders, same formula of [83] was utilized.

The sensible and total enthalpies are:

$$h = h_{ref} + \int_{T_{ret}}^{T} (C_p)_{nf} \mathrm{d}T \tag{5}$$

$$H_e = h + \lambda L \tag{6}$$

where h_{ref} is the enthalpy at $T_{ref} = 273$ K.

λ should be obtained from the below formula:

$$\lambda = \begin{cases} \frac{T_s - T}{T_s - T_l} & T_s < T < T_l \\ 0 & T < T_s \\ 1 & T < T_l \end{cases} \tag{7}$$

Mesh sample is shown in Fig. 1 and to obtain better convergence, structure grid was utilized. Enthalpy–porosity method which is defined in ANSYS FLUENT was employed in this article [82]. For pressure correction, we utilized PRESTO algorithm.

3 Results and discussion

In current article, to improve the melting inside a tank, a spiral pipe was added in which hot fluid flows and helps with melting process. FVM was applied to simulate this process, and verification in view of values of liquid fraction is demonstrated in Fig. 2. As depicted, nice agreement with Ref. [84] was obtained and it proves the accuracy of current code. Distributions of temperature for various parts are depicted in Fig. 3 when Re = 500. Fluid inside the spiral pipe becomes colder and makes the solid paraffin to melt. As time progress, the liquid parts appear, and in this zone, the buoyancy force helps to faster melting. So, outlet temperature of fluid reduces when exiting the spiral. It is obvious that NEPCM domain has lower temperature in comparison with fluid inside the spiral. Temperature of nanofluid augments till time progresses to $t = 10$ min. Also, T_{NEPCM} zone reaches to constant value after melting becomes completed.

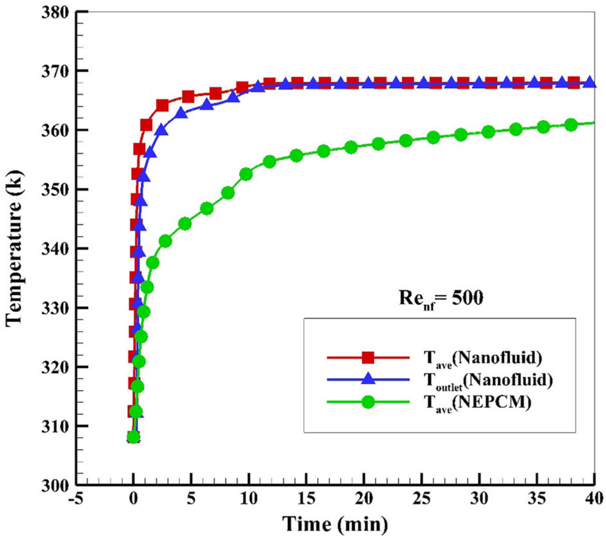


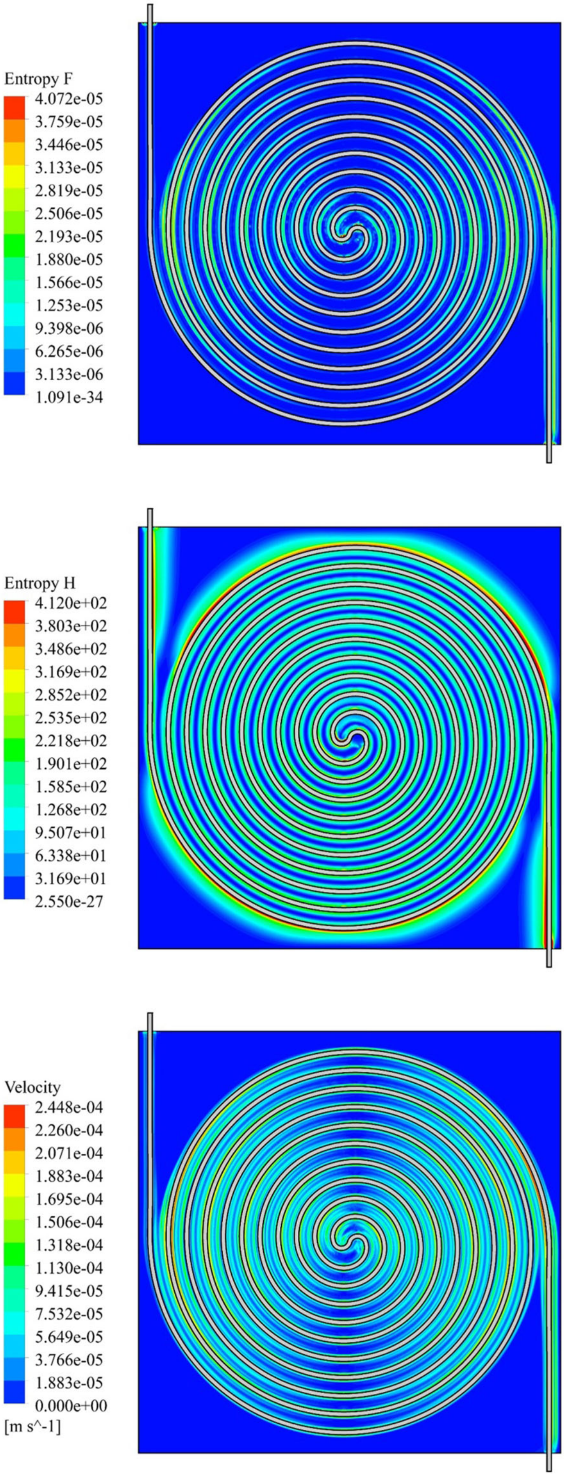
Fig. 3 Temperature distribution history in various parts

This type of system is very common in industry due to its easier cleaning of HTF pipes. Nanopowders were dispersed to augment thermal behavior (not only in fluid flows in pipe but also in PCM). Figures 4, 5 and 6 illustrate the velocity, $S_{gen,f}$ and $S_{gen,th}$ contours when $Re = 500$. In addition, we increased the Re to 1000 and extracted the contours as depicted in Figs. 7, 8 and 9. The main goal of designers is reaching to lowest irreversibility, and by finding these regions with grater entropy during process, they can remove that fault. Buoyancy force acts in this process and affects the speed of melting. In initial time, the hot nanomaterial in pipe creates the great flux and affects the boundaries, and after about 5 min, the heat flux reaches to its highest values and then reduces and finally reaches to constant value. Due to jump in velocity gradient in initial time ($t < 5$min), $S_{gen,f}$ increases suddenly and then decreases. As time progresses, eddies generate near the outer side of spiral which provide greater temperature gradient and lower $S_{gen,th}$. Augmenting inlet velocity makes heat flux to decrease which creates stronger temperature gradient, and more thermal irreversibility appears in contours. Increasing pumping power has no sensible effect in greater time, while it has supportive effect in middle time of process. Velocity and $S_{gen,f}$ have direct relation in view of regions with greater values because the main term of frictional irreversibility is velocity gradient. As depicted in contours of $t = 5$min, the uniform distribution of $S_{gen,th}$ exists in this time. Melting starts from inner spiral, and the outer side was the last regions which convert from solid to liquid. The zone near the below wall takes more time to melt because in this region, free convection is poor.

4 Conclusion

Spiral heat exchanger is employed inside a tank to accelerate melting process. To rise the thermal behavior of PCM and H_2O, nanopowders are dispersed in both of them. The focus of this research is irreversibility of NEPCM during charging. Results indicate that heat flux which affects the NEPCM has sudden increment at initial time, but it reduces with progress of time.

Fig. 4 Contours of velocity, $S_{\mathrm{gen,f}}$ and $S_{\mathrm{gen,th}}$ when Re = 500, t = 5 min



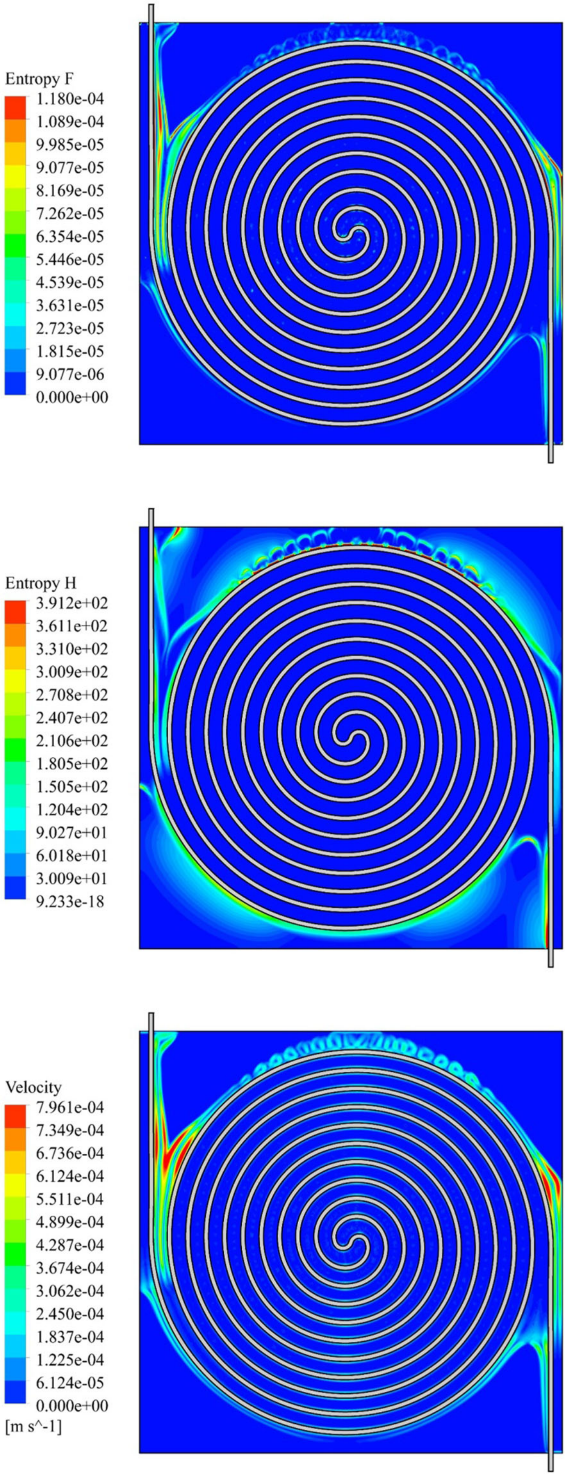
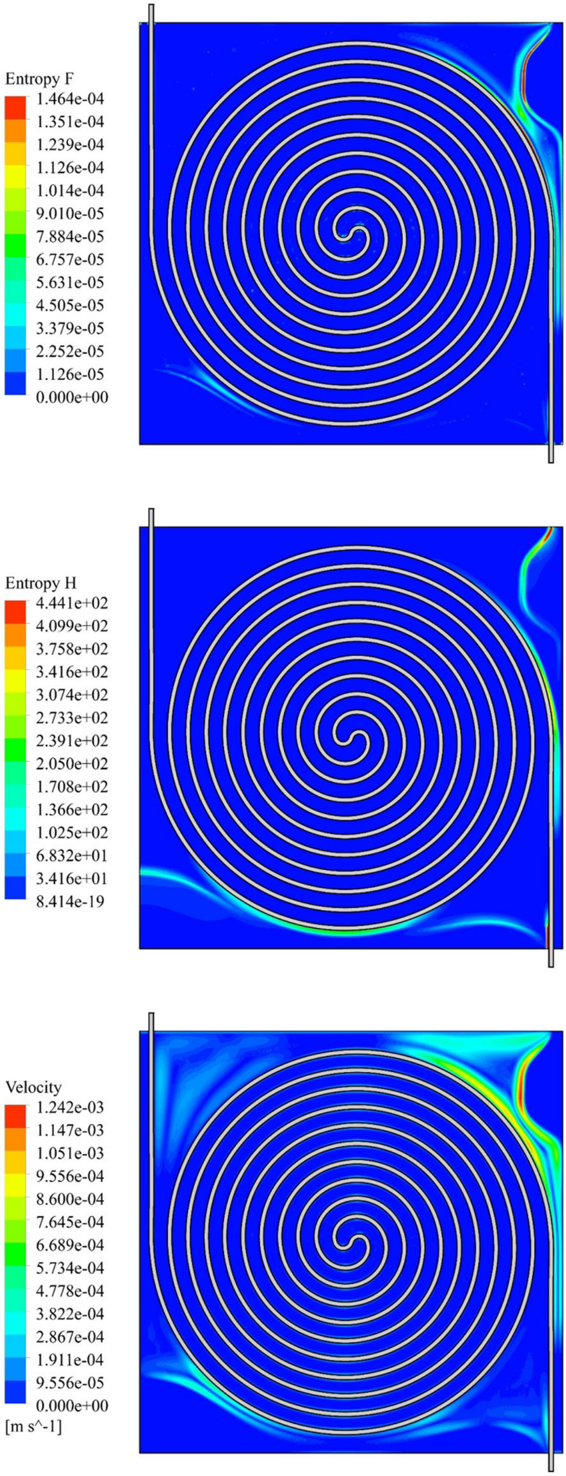


Fig. 5 Contours of velocity, $S_{gen,f}$ and $S_{gen,th}$ when $Re = 500$, $t = 20$ min

Fig. 6 Contours of velocity, $S_{gen,f}$ and $S_{gen,th}$ when $Re = 500$, $t = 80$ min



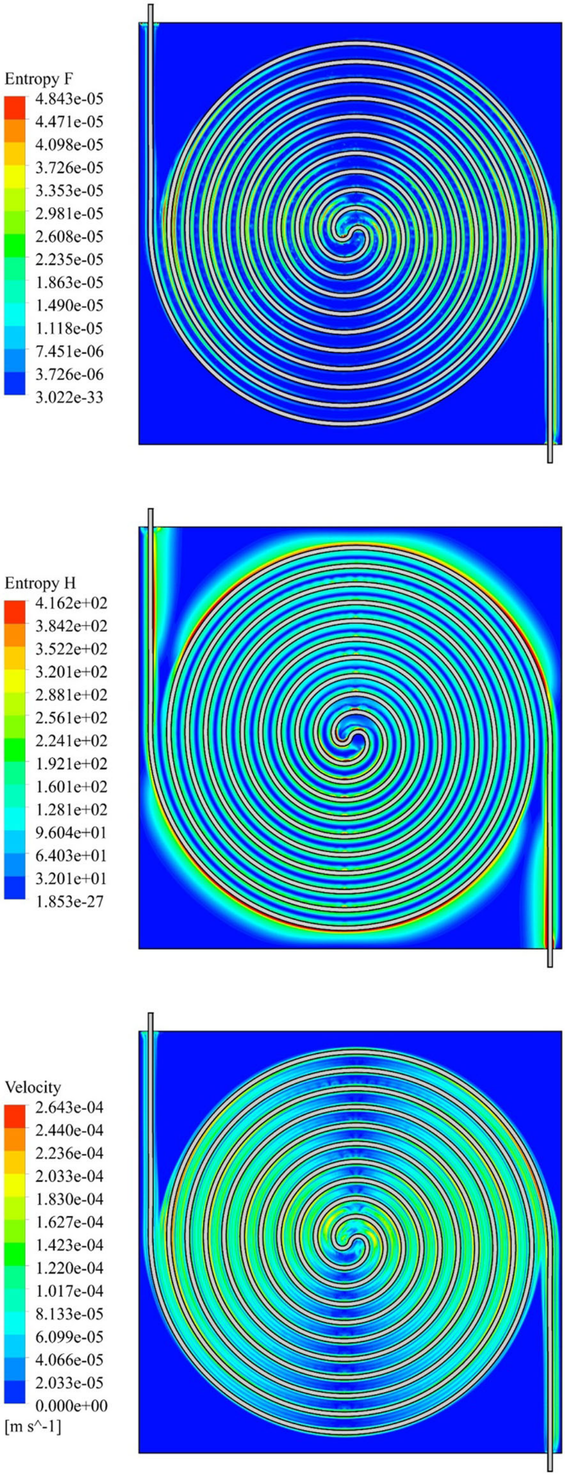
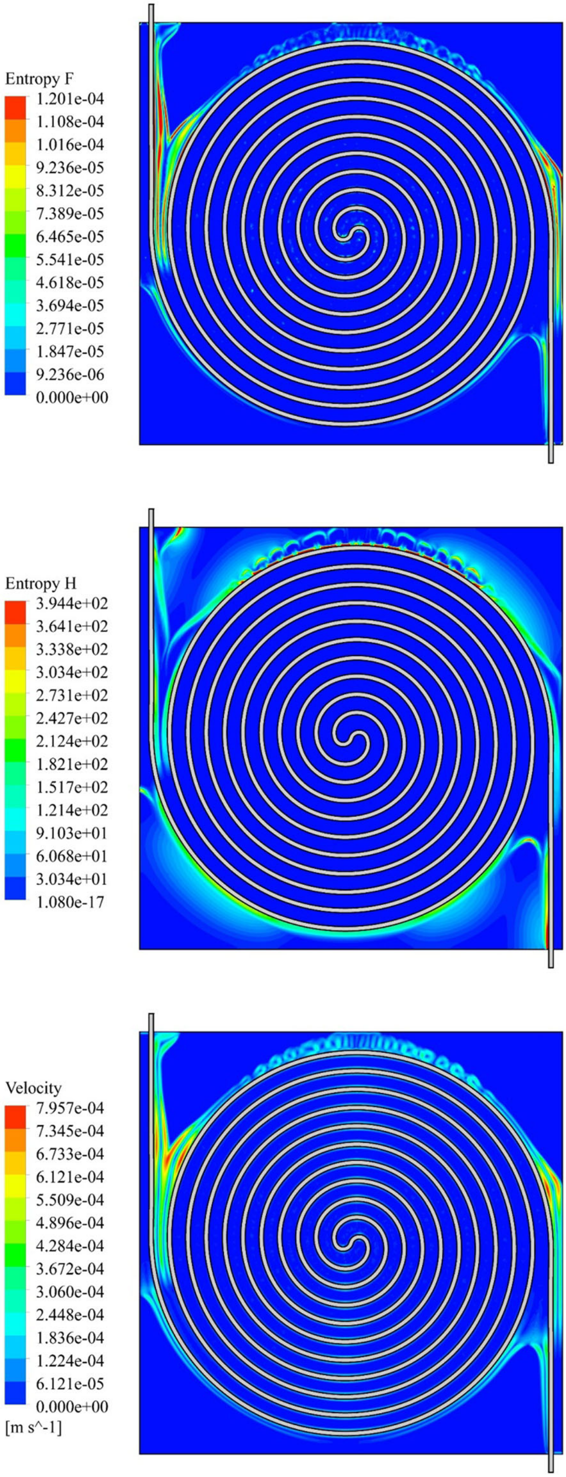


Fig. 7 Contours of velocity, $S_{\mathrm{gen,f}}$ and $S_{\mathrm{gen,th}}$ when $\mathrm{Re} = 1000$, $t = 5$ min

Fig. 8 Contours of velocity, $S_{gen,f}$ and $S_{gen,th}$ when Re $= 1000$, $t = 20$ min



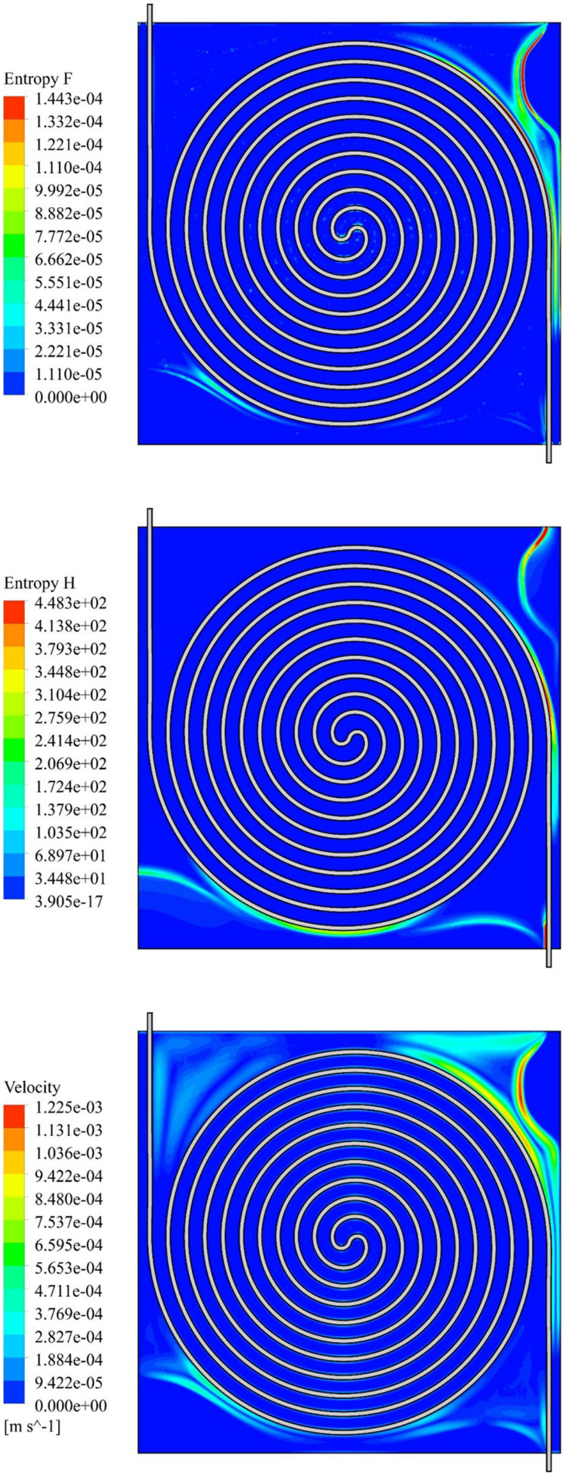


Fig. 9 Contours of velocity, $S_{\text{gen,f}}$ and $S_{\text{gen,th}}$ when $\text{Re} = 1000$, $t = 80$ min

Thermal irreversibility reduces during charging which attributes to increasing temperature of NEPCM.

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