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Experimental and numerical studies of a fatty acid based phase change dispersion for high voltage electrical devices cooling enhancement

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Abstract

A fatty acid based phase change dispersion (PCD) for efficient high voltage electrical devices cooling has been developed and investigated in this paper. Experiments were firstly conducted to measure the PCD thermophysical properties and to detect the bulk fluid and inner wall temperature of PCD flowing in a circular pipe by a self-designed rig. A 3D modelling based on the Euler-Euler model and homogenous single-phase model were then performed and validated through experiments, and further employed to evaluate the effects of particle size, concentration and operating conditions on flow characteristics, pressure drop, heat transfer and energy transport performance of the PCD. The results showed that both the particle size and concentration presented significant influences on heat transfer between the two phases, and average friction factor as well as heat transfer coefficient of the PCD. The higher averaged Nusselt number and larger pressure drop appeared when the PCM particle diameter decreases to 7 μm . For the investigated conditions in this work, an optimal set of cooling performance for the developed fatty acid PCD was proposed and a PCM particle size of 7 μm under a flow velocity of 4 m/s and a concentration of 35% was recommended for industrial cooling applications.

Keywords: Fatty acid; Phase change dispersion; Euler-Euler; Heat transfer; Cooling enhancement; Energy transport;

1. Introduction

High electrical power demand requires a continuous effort to miniaturise High-Voltage Direct Current (HVDC) devices, which can have a heat flux approaching the megawatt range and is beyond the domain of conventional thermal management technologies [1, 2]. Power dissipation of 9.72 kW has been detected in a high power HVDC transmission system in which power converters turn AC to DC and vice versa through controllable electric switches. Such switches take up to 30% of the whole loss power [3, 4]. Although the power module failure rate due to electronic converter instability has dropped in recent decades, it still causes tremendous economic loss and plant maintenance costs [5]. For high power electronic devices, an option for thermal performance enhancement is the dispersion of Phase Change Material (PCM) in an immiscible thermal-active fluid – the so called phase change dispersion (PCD). Under a targeted set of operational conditions, the PCD can be designed to enhance the thermal performance with a uniform temperature distribution and a small temperature change [6-9].

For industrial applications of the HVDC cooling, the PCD is best to be electrically insulating to ensure long-term lifespan in a high voltage environment. As a type of organic dielectric material, fatty acid has been widely considered due to its low chemical inertness, self-nucleation during phase change and with a low electrical conductivity [10, 11]. Such material normally works in the ambient-to-moderate temperature range [12] (20-100 °C), which is suitable for HVDC electronic devices cooling [13] (around 60 °C). The electrical conductivity of the fatty acid can reach as low as 10^{-10} S/m [14]. To make PCM long-term stable miscible with water, a small amount of emulsifier composed of a hydrophilic head group and a hydrophobic tail should be added, so that problems such as coagulation, coalescence or Ostwald ripening [15] can be resolved. Numbers of dielectric emulsifier have been studied, such as fatty acid [16] and graphene oxide [17]. The introduction of nucleation agent reduces the super cooling problem in PCD. The most popular nucleation agents are octadecanol [18-20] and paraffins [21-23] etc. Emulsions are usually fabricated in high energy environment like high-shear mixer or ultrasound generator. The choice of particle size is a trade-off between PCM stability and super cooling [24].

A dilute PCD often shows a Newtonian behaviour, but can be highly non-Newtonian when the emulsion concentration is increased. There is however no clear demarcation in terms of the concentration. For example, a 30 w/w % tetradecane emulsion [36] is found to be Newtonian fluid, while the behaviour of a paraffin/water emulsion [21] is pseudo-plastic with a mass fraction from 15 % to 50%. Therefore the PCD rheology is hard to be judged empirically. The viscosity of emulsions may be 2–550 times that of water [25, 26], yet the increased pressure drop has been found to barely affect the pumping work [27, 28]. The correlations of friction factor have been proposed either empirically based or from physical

models originated from the fluid-wall interactions. A comprehensive comparison of friction factor correlation has been provided by Prieto et al. [29], Babajimopoulos and Terzidis [30] and Brkić [31]. It is noteworthy that most correlations were developed under isothermal condition while the oscillation of fluid properties during phase change is still unclarified.

To use PCD in typical applications such as heat exchanger, the flow characteristic studies are needed to understand its effectiveness in heat transfer. Most studies were carried out for ice slurry or water-glass/sand system at low concentrations. Vuarroz et al. [32] studied the velocity and temperature profiles of ice slurry for 13–19 v/v %, using Ultrasonic Doppler Profiler. Campbell et al. [33] conducted concentration measurement of glass beads in water around 20 v/v % , and found the lift force may alter the solid distribution. Stamatiou and Kawaji [34] measured the velocity profiles of 0–9 w/w % ice slurry from three positions along the vertical pipe using a hot film probe, but the limited information was insufficient for the flow characteristic study. Kaushal et al. [35] evaluated the concentration and velocity profile of glass beads in water, and found particle size influences the degree of asymmetry in concentration profile. Due to the complexity of performing local concentration and velocity measurement in insulated pipes, the numerical simulation was widely used to study the flow characteristics. The Euler-Euler model is an expensive but fruitful tool to deal with the two-phase nature than the single-phase model. Wang et al. [36] studied ice slurry (< 25 v/v %) in horizontal, vertical and 90 ° elbow pipe using Euler-Euler model, with a simple and cheap algebraic equation for granular kinetic calculation which neglecting convection and diffusion. The PCM slurry [7] and slush nitrogen [37] were also tested, but the particle distribution on viscous sub-layer (which will affect wall temperature) was easily missed.

For heat transfer characteristics of PCD, many Nusselt number correlations are proposed based on the assumption of single-phase Newtonian fluid. But it is questionable whether this assumption validates for high PCD concentrations or turbulent flow. Moreover, the influence of phase change on overall heat transfer coefficient is not clarified. Several literatures indicate the importance of Stefan number in PCM heat transfer[38, 39]. The Stefan number is defined as the ratio of sensible heat to latent heat, $Ste = \frac{C_{p,s}|QD/2k_s|}{\Delta h_{pc}}$, given under the boundary condition of constant heat flux. Wang et al. [40] proposed the correlations of microencapsulated PCD by including Ste, for laminar flow and low Re number ($2100 < Re < 3500$) turbulent flow. Ho et al. [41] developed heat transfer correlation of MPCM particles in terms of Plect number, Ste and inlet subcooling parameter, for laminar condition ($133 < Re < 1515$) and low mass fraction of 0 – 10 wt.%. The correlations under turbulent flow and high concentration are still needed for PCD performance improvement.

To fulfil the cooling requirement of an industrial HVDC converter proposed by GEIRI GmbH (Germany), a novel PCD is designed to have phase transition temperature and melting temperature in the range of 30-60 °C and 47.5-50 °C, respectively, where the PCD specific

heat capacity should be doubled over water. The electrical conductivity of proposed solution is expected to be nearly zero to ensure long-term applicability in the high voltage environment. In view of this, a fatty acid-based PCD that suitable for efficient high voltage electrical devices converter cooling is developed and investigated experimentally and numerically in this work. Experiments were firstly conducted to measure the PCD thermophysical properties and to detect the bulk fluid and inner wall temperature of PCD flowing in a circular pipe by a self-designed rig. Both a 3D Euler-Euler multiphase model and a homogenous single-phase model were then developed and validated by the experimental results, and further employed to evaluate the PCD thermal characteristics. The influence of particle size, PCM concentration and inlet velocity on flow characteristics, pressure drop and heat transfer as well as energy transport performance were discussed detailedly. The results presented in this work provide an efficient and economical solution to cool down the HVDC converter in high voltage environment, and contribute to the development of PCD in the thermal management fields.

2. Experimental measurements

2.1. PCD preparation and properties characteristics

An extensive screening of the PCD system has been done to reach the industrial HVDC cooling requirement. A mixture of commercial fatty acid esters (50% Crodatherm 53 +50% Crodatherm 47, from Croda International PLC, UK) and ethoxylated fatty alcohols (75% Steareth-100 + 25% Steareth-2, from KLK Oleo, Germany) were used as PCM and emulsifier, respectively. A small portion (1.6 w/w%) of glycerol was added in the deionized water to form the continuous phase. The optimal PCD composed of 16 w/w % of PCM, 4w/w % of emulsifier, 0.5 w/w% nucleation agents in continuous phase. The dispersion was manufactured by dispersing PCM phase into deionized water using a Polytron 10-35 GT lab rotor-stator in Lucerne University of Applied Sciences and Arts, Switzerland.

The thermo-physical properties of PCD components under solid and melting conditions were measured at Birmingham Centre for Energy Storage (BCES) in University of Birmingham, and the results were tabulated in Table 1. Each measurement was repeated at least 3 times to ensure reproducibility. The solution density was measured using an Anton-Paar DMA 4100M density meter (UK), with 2 mL samples held at desired temperature for 10 minutes. The thermal conductivity was determined from a Netzsch LFA 427 (Laser Flash Analysis, German) output signal using refined Cowan model [42]. Each measurement was carried out with a laser voltage set point of 480 V and laser pulse width of 80 ms. The specific capacity, melting point and phase change enthalpy melting were determined using a Differential Scanning Calorimeter (DSC2, Mettler Toledo, USA). Tests were performed from 298.15 K to

338.15 K with a heating rate of 5 K/min in Platinum crucibles under nitrogen atmosphere and a purge flow of 100 mL/min. Samples were held at constant 298.15 K and 338.15 K for 20 minutes, and repeat the heating cycles for 4 times. For statistical studies, samples varies 15-20 mg were prepared and each sample was tested three times. The specific heat capacity was obtained according to the standard (DIN51007) by the sapphire method. The heat capacity plots with temperature under different PCM volume fractions ($\phi = 0.05, 0.1, 0.2$ and 0.35) are given in Fig. 1. The PCD stability against creaming, sedimentation and coalescence was also studied by an optical centrifuge of LUMiSizer, and the results demonstrated the sufficient stability of the proposed PCD even experienced more than 200 cycling times.

Table 1. Thermo-physical properties of water and PCD components under solid and liquid condition.

	ρ [kg/m ³]		k [W/(m·K)]		c_p [kJ/(kg·K)]		T_{melt} [°C]	Δh_{pc} [kJ/kg]
Working Temperature[°C]	25	55	25	55	25	55	-	-
Water	998.2	988.4	0.61	0.651	4.18	4.18	-	-
PCM	902	827.2	0.231	0.206	2.78	2.38	47.13	193.38
Emusifier	1011.4	1005.3	0.293	0.301	2.28	2.21	49.72	141.53
PCD	983.9	980.5	0.529	0.561	3.82	3.78	50.95	26.11

a)

Fig. 1. a) DSC measurement of PCM and emulsifier, b) C_p variation with temperature of different PCM concentration, $\phi = 0.05, 0.1, 0.2$ and 0.35 .

A rotational MCR 502 rheometer (Anton Paar, UK) equipped with a convection oven and a temperature controller (TC30) was performed to quantify the rheology behaviour of PCD components. The measurements (repeated 3 times) were carried out using 2.0 samples in a stainless-steel parallel plate of 35 mm diameter fitted in a concentric cylinder of 40 mm diameter. The controlled sample amount was required to ensure a constant measurement contact area, and any excess sample will be removed after the shaft reaching its measuring position. The motor is required to warm up to 17000 s^{-1} before any measurement conducted, followed by motor adjustment and calibration to ensure reliable data. Each test was conducted over a shear rate from 0.1 s^{-1} to 200 s^{-1} under constant airflow rate of 1 L/min . The measurement deviations are less than 2.3 %. The rheology of PCD follows non-Newtonian fluid characteristic, as given in Fig. 2. With increasing shear rate, the PCD viscosity decreases whether melted or not. However, the viscosity can reach up to $10000 \text{ mPa}\cdot\text{s}$ at low shear rate ($< 25 \text{ s}^{-1}$) when PCD melted (323.15 K and 328.15 K), acting like rigid material.

Fig. 2. Rheology behaviour of PCD under various a) shear rates, $\phi = 0.2$ and b) temperatures, $\gamma = 100 \text{ s}^{-1}$.

The Herschel-Bulkley model [43] is introduced to describe the Non-Newtonian PCD behaviour, which combines models of Bingham plastic ($n=1$) at low shear rate and power-law at higher shear rate. The yield stress threshold $\tau_0 = 24 \text{ s}^{-1}$ was derived from the experimental rheology results, and the critical shear rate $\dot{\gamma}_0 = 0.3782 \text{ Pa}$ and consistency factor $k = 2.316 \text{ Pa}^n$ are determined using least square regression method. Thus the relationship of PCD viscosity and shear rate can be expressed as:

$$\mu_0(\gamma) = \begin{cases} \frac{0.3782}{\gamma} + 0.002316 \text{ (Pa} \cdot \text{s)}, & \gamma > 24 \text{ s}^{-1} \\ 0.0332 - 0.000657\gamma \text{ (Pa} \cdot \text{s)}, & \gamma < 24 \text{ s}^{-1} \end{cases} \quad (1)$$

To include the temperature dependency, the Arrhenius law is adopted as $\ln H(T) = C - E_\alpha/RT$, where E_α is the activation energy and R is the universal gas constant equal to $8.314 \text{ J}/(\text{mol}\cdot\text{K})$. The best fit curve based on experimental data of $\ln H(T)$ and $1/T$ yields activation energy of $E_\alpha = 56.868 \text{ kJ/mol}$. The high activation energy means fluid is less sensitive to temperature changes, because high energy is needed to overcome the strength of the inter-particle forces that keep the floc network together [44]. Actually the temperature effect on viscosity is rather small given the small viscosity oscillation in Fig. 2b). The correlated PCD viscosity shows good agreement with the experimental value (average deviation of 10.19 %), as given in Fig. 3. The error bar represents the viscosity deviation caused by temperature.

Fig. 3. Comparison of experimental data and model results on PCD viscosity ($\phi = 0.2$).

The size distribution is measured with a Zetasizer Nano-ZS dynamic light scattering (Malvern, UK) in BCES of University of Birmingham. Tests were performed with a 173° scattering angle and repeated 3 times with small deviation up to 2.05%. The particle size ranges between $0.065 \mu\text{m}$ and $7.3 \mu\text{m}$, as shown in Fig. 4.

Fig. 4. Relationship of particle volume fraction and particle diameter.

2.2. Test-rig

The heat transfer experiment of PCD was conducted at Lucerne University of Applied Science and Arts (Switzerland). The fluid was transported by an impeller pump (Zuwa NIROSTAR/V 2000-B/PT, Germany) into a circular pipe with a total length of $L = 16$ m, inner diameter of $D = 0.014$ m and outer diameter of 0.02 m. A Coriolis flow meter (Promass F83, Endress + Hauser AG, Switzerland) was used to control the mass flow with uncertainty of $\pm 0.004 \dot{m}$, where $\dot{m}$ is the mass flow rate. The uniform heat flux was obtained by wrapping a heat cable (TWIN, Arnold Rak GmbH, Germany) with diameter of 3.37 mm right next to the pipe out wall, and thermal insulated by an aluminium foil together with PIR shells (Swisspor, Switzerland) of 50 mm thickness. The maximum thermal power of the heat cable is 4 kW, which is powered by a thyristor power controller (TYA-201, JUMO Co Ltd, UK) that allows precise control of heat input with uncertainty of $\pm 0.02 P_{el}$ (P_{el} is the electrical power). The wall and bulk temperature were measured by the Pt-100 four-wire thin film sensors, with measurement uncertainty less than ± 0.03 K. The temperature measurements for the pipe wall and fluid were derived directly from the thermocouples, and the heat transfer coefficient was then straightly determined. The scheme of the test-rig is given in Fig 5 and the detail of measuring section can be found in Ref [45]. To determine the system heat losses, the setup was first tested with water under various $\dot{m}$ and P_{el} . The heat loss, identified as the difference between P_{el} and sensible heating of water from inlet to outlet $Q_{loss} = P_{el} - \dot{m}(C_p T_{out} - C_p T_{in})$, was determined to be 40 W on average, which will be used for the PCD calculation.

Fig. 5. Schematic of the experimental test-rig.

3. Numerical modelling

3.1. Mathematical model

In this work, two-phase Euler-Euler model and single-phase homogenous model are used to calculate the flow characteristic of PCD. The motivation of using homogenous model is better thermal prediction than the two-phase models for nanofluid turbulent flow [46, 47], with low computational cost. However, similar comparison was less conducted for PCD, especially with the measured thermos-physical properties. The 3D computational domain was setup with the same cross-section geometry as experimental test section, and total length of $L = 5.5$ m to reduce computational cost for the fully developed flow. The inlet temperature was chosen just below the PCM solidus point $T_{in} = 316.86$ K. The simulation heat flux, which is subjected to equipment power, was increased to $Q = 80000$ W/m² so that PCM can be fully melted.

In Euler-Euler model, the fatty-acid PCM particle and glycerol-water solution are treated as interpenetrative continua, coupled through the interphase momentum and heat transfer. The PCD are treated as incompressible turbulent flow, and the PCM particle is assumed to be smooth, inelastic and spherical during the phase change condition. The $k-\omega$ turbulence model with shear stress transport (SST) model is used due to their proven accuracies in solving mixture problems in the near-wall region [48, 49]. The accurate prediction of $k-\omega$ SST model is dependent on the high quality meshed grid. In this work, the 3D domain is structured with hexahedral cells in pipe core and refined mesh near wall, to ensure the wall coordinate y^+ is near 1 in the sublayer, as shown in Fig. 6. The mesh growth rate is fixed to 1.15 until it

reaches the log-law layer. It is found that as the number of nodes per cross-section increases from 546 to 1002 and from 1002 to 1418, the temperature at monitored points changes by 3.56% and 0.74% respectively. Thus the 1002 nodes are good enough to ensure calculation accuracy without consuming too much computational source, and are chosen for further calculations. The mathematical models used in the present study are summarized in Appendix, which are divided into 4 categories: governing equations (Eqs. (A1)-(A4)), kinetic theory of granular flow (Eqs. (A5)-(A12)), energy equations (Eqs. (A13)-(A16)) and the near wall boundary condition (Eqs. (A17)-(A18)).

Fig. 6. Photographs of the mesh sizing with cross-section view (a) and enlarged side view (b).

The sensitivity analysis have been carried out to test the kinetic models for granular flow, and here only the confirmed one are presented in the Appendix table. The fluctuating particle motion is described by the granular temperature, and the maximum volume fraction is chosen to be 0.52 [50]. The virtual mass force can be neglected because the density difference between solid and liquid phase is less than 15%. As the dominate force in per phase, the drag force (Eq. (A10)) is described by Syamlal and O'Brien [51] model. The lift force force (Eq. (A11)) acts on area of high velocity gradient (such as the near wall regime) and calculated via Saffman [52] model. The particle distribution is dominated by the turbulent dispersion force (Eq. (A12)) when the size of turbulent eddies are larger than the particle size, and the dispersion coefficient C_{td} is generally determined to be 1 in Simonin and Viollet [53] model. The particle-particle restitution coefficient e_{ss} is chosen to be 0.9. The volumetric heat transfer coefficient force (Eq. (A14)) is estimated based on the correlation proposed by Gunn [54].

At the near wall regime, the no-slip condition is used for liquid phase, and the Johnson-Jackson wall boundary conditions (Eqs. (A17) and (A18)) are employed for solid phase. The particle-wall restitution coefficient and specularity coefficient are adjusted between 0.0001-0.001 and 0.9-0.99 respectively to ensure mass balance for various conditions. The

discrepancy of solid distribution and velocity caused by coefficient differences has been proven to be very small [37]. The residuals were below 10^{-5} under all calculation conditions, and the energy residuals were less than 10^{-13} when converged. The detail discussion of discretization schemes and coupling correlations of Euler-Euler can be found in previous papers [37, 55, 56] thus not given here. For homogenous model, the optimal combination [46] of the effective properties correlations are given in Table 2.

Table 2. Correlations of effective properties used in homogenous model

Properties	Equation	Reference	Eq. No
Density	$\rho = (1 - \phi)\rho_l + \phi\rho_s$	Khanafer et al. [57]	(2)
Viscosity	$\mu = (1 + 7.3\phi + 123\phi^2)\mu_l$	Maïga et al. [58]	(3)
Specific heat	$C_p = \frac{(1 - \phi)(\rho C_p)_f + \phi(\rho C_p)_s}{\rho}$	Khanafer et al. [57]	(4)
Conductivity	$\frac{k}{k_l} = \frac{[k_s(1 + 2\alpha) + 2k_l] - 2\phi[k_l - k_s(1 - \alpha)]}{[k_s(1 + 2\alpha) + 2k_l] + \phi[k_l - k_s(1 - \alpha)]}$	Nan et al. [59]	(5)

3.2. Model validation

To ensure reliability of the present Euler-Euler model, validations are conducted against the hydrodynamic features derived from literature and the temperature measurement from the present experiment. Fig. 7 compares the radial distribution of glass particles from the present model with the experimental data from Kaushal et al. [35] and simulation results from Wang et al. [36] and Bordet et al. [49]. Simulations are performed at isothermal condition ($T = 293.15$ K) to match respective experiments, using mesh grids similar to the present one. The particle profiles are extracted at $x/L = 9/10$ to ensure fully developed flow. For small particle ($d = 125$ μm), as given in Fig. 7a), the present work and model from Bordet et al. [49] agree well with experimental data, but Wang et al. [36] over-predicts the concentration gradients with a deviation of 16.13 %. With increasing particle sizes and higher loadings, as shown in Fig. 7b) and 7c), the particle repelling near the pipe bottom can be captured by the present work and Wang et al. [36], but the turning point from Wang et al. [36] sits far away from the bottom wall and conflicts with experimental trend. The average deviation of the present work and Bordet et al. [49] from experiment is 11.91% and 8.32% , respectively, but the latter one fails to capture the near wall particles. The relative large deviation from Wang et al. [36] is caused by the coarse grid near pipe wall and inappropriate transport equation. They used a simple and cheap algebraic equation but neglecting convection and diffusion. The turbulent

dispersion term from Bordet et al. [49] counter-balanced the sedimentation phenomenon, resulting in a more homogenous concentration profile but miss the repelling near wall.

The velocity profiles of fully developed ice slurry flows were also compared with experimental measurements from Vuarnoz et al. [32]. As given in Fig. 7d), the average deviation of the present work and experimental data is 2.83%, which is comparable with Wang et al. [36] model (deviation of 2.31%). The lowest deviation (1.12 %) from experiment can be derived from Bordet et al. [49], because they used turbulent dispersion term of Phillips et al. [60]'s equation to stabilize the flow calculation. Overall, all three models compares fairly well to the experimental velocity.

a)

b)

c)

d)

Fig. 7. a-c) Comparison of radial distribution of glass particle at $U_{in} = 4$ m/s of a) $\phi_{in} = 0.1$, $d = 125$ μm , b) $\phi_{in} = 0.1$, $d = 440$ μm , c) $\phi_{in} = 0.2$, $d = 440$ μm ; d) Comparison of radial distribution of mean axial velocity.

The measured bulk and wall temperatures along the 16 m pipe were compared with Euler-Euler model and homogenous model under $Q = P_{el} - Q_{loss} = 3160$ W. For homogenous model, the thermos-physical properties including density, thermal conductivity, specific heat, Herschel-Bulkley viscosity were implemented with the Realizable k- ϵ model and enhanced wall functions. The water properties were incorporated in FLUENT as polynomial function with coefficients listed in Table 3, which validated in the range of $283.15 \text{ K} < T < 613.15 \text{ K}$.

On Fig. 8, the single-phase predictions of the bulk flow are satisfactory but the wall temperature is significantly lower than the experimental data. The model yields average wall temperature difference of 1.18 K, which accounts for 33.34% of the total wall temperature increment (from inlet to outlet). It may be attributed to the ignorance of near-wall particle distribution inside a homogenous particle field. The Euler-Euler model has a shorter calculation domain ($L = 11$ m) due to numerous mesh grids, and overall compares fairly well to the experimental data, with deviations up to 8.47 % on total temperature increment. Thus the hydro- and thermo- dynamic features of PCD can now be confidently studied using the Euler-Euler model.

Table 3. The coefficients of polynomial function of water properties at 155bar.

ϕ	A_1	A_2	A_3	A_4	A_5
ρ [kg/m ³]	1.351E+03	-2.422	6.32E-03	-6.989E-06	
k [W/(m·K)]	-2.946E-01	4.757E-03	-5.712E-06		
c_p [J/(kg·K)]	6.515E+01	-6.166E-01	2.299E-03	-3.755E-06	2.276E-09
μ [kg/(m·s)]	3.738E-02	-3.093E-04	9.609E-07	-1.320E-09	6.746E-13

$$\phi(T) = A_1 + A_2 T + A_3 T^2 + A_4 T^3 + A_5 T^4$$

Fig. 8. Comparisons of wall and bulk temperature from experimental measurements, Euler-Euler model and homogenous model, $\phi = 0.2$, $U_{in} = 0.95$ m/s.

4. Results and discussion

Having verified the confidence of numerical model, the influence of particle size, PCM concentration and inlet velocity on flow characteristics, pressure drop, heat transfer and energy transport performance were discussed detailedly. The flow characteristic were studied under isothermal condition, where PCM particles are kept at liquid state at $T = 338$ K.

4.1. Flow characteristic of the PCD

4.1.1. Influence of PCM particle size

Fig. 9 shows the fully developed PCM concentration and velocity profiles along the vertical symmetric axial for different particle sizes at $U = 0.95$ m/s and $\phi_{in} = 0.2$. On Fig. 9a), the constant concentration profile of $7 \mu\text{m}$ particle indicates homogenous flow. For the diameter of $70 \mu\text{m}$, particle is small enough to follow the turbulent eddies, but no longer fits completely in the thin viscous sub-layer. Thus the dispersion flow is very close to a homogenous distribution in the pipe core, with a very thin layer of particle accumulation near the wall. The flow pattern progresses to heterogeneous flow with the increase of particle diameter ($200 \mu\text{m}$), with PCM concentrated at upper zone due to buoyancy. The $d = 400 \mu\text{m}$ flow can be referred to a stationary bed like flow regime. The maximum packing factor ϕ_{max} locates at the inflexion point, where the profile gradient changes suddenly. The inflexion gradually shifts away from the wall with increasing particle diameter, from $\phi_{max} = 0.23$ at $y/D = 0.403$ for $d = 200 \mu\text{m}$ to $\phi_{max} = 0.34$ at $y/D = 0.29$ for $d = 400 \mu\text{m}$.

The near wall particle distribution deserves careful treatment as it may significant influent the wall temperature. Along with the top of the pipe, the concentration profile of starts with a near-wall peak, because the turbophoresis [61] drives a net particle flux towards the wall. The peak has the highest value for moderate particle size ($70 \mu\text{m}$), decreasing from $\phi_{peak} = 0.32$ for $d = 70 \mu\text{m}$ to $\phi_{peak} = 0.13$ for $d = 400 \mu\text{m}$. Then particles migrate away from the wall due to collisions with particles adhering to the walls, leading to a local concentration reduction ϕ_{low} at the turning point. The turning point slightly drifts away from the wall with the increase of particle size, but overall the thickness is less than millimetres. When comes to the streamwise region, the turbulent and buoyancy take over the dispersion of PCM particles, which show the tendency to float upwards.

Fig. 9b) compares the velocity profiles along the vertical symmetry axis under different particle diameters. It is clear that the velocity profile is symmetry for the small ($7 \mu\text{m}$) and moderate ($70 \mu\text{m}$) particle. A slight asymmetry is observed with larger size ($200 \mu\text{m}$) in the upper half of the pipe due to higher PCM concentrations. For $400 \mu\text{m}$ particle, the particle-particle collision and turbulent dispersion of particle clusters near the top wall result in a steep velocity gradient. The velocity gradient causes a strong shear stress to repel the particles away from upper wall, leading to a drifting inflexion point. In the lower half of the pipe, PCM concentration decreases and the near-wall particle effect still results in a location

concentration reduction. Similar phenomenon was also reported in ice slurry flow by Wang et al. [36] and Bordet et al. [49], but both of them failed to capture the near-wall particle peak, due to the simplified algebraic slip model[36] and homogenized turbulent dispersion term[49], respectively.

a)

b)

Fig. 9. a) PCM concentration and b) velocity profiles along the vertical symmetry axis for $U = 0.95$ m/s and $\phi_{in} = 0.2$ at $x/L = 9/10$, $d = 7, 70, 200$ and 400 μm .

To have a further insight into the hydrodynamic feature, Fig. 10 represents profiles of the axial velocity, PCM volume fraction, radial water and PCM velocity field under different particle sizes for $U = 0.95$ m/s, $\phi_{in} = 0.2$. Only half of the symmetric pattern is presented for the fully developed flow. In general, the radial water velocity is very similar to the PCM one

expects for the boundary layer regime, but both magnitudes are significantly smaller than that of the axial velocity. The secondary flow, driven by the non-uniform force of the flow induced by the solids entrained in fluid core, is captured under various particle sizes. The intensity of secondary flow and radial velocity increase with the growth of particle diameter.

Increasing particle size (from 7 μm to 70 μm) leads to a concentration and velocity gradient near the pipe wall, as shown on Fig. 10b) and 10f). This is attributed to the fact that the particle also have a considerable effect on turbulence flow through momentum exchange (i.e. two-way coupling), as well as the near wall effects. With increasing particle diameter, a high axial velocity and PCM concentration region can be visualized in the upper half of the pipe on Fig. 10c) and 10d). Interestingly, the regime of main vortices (circular regime between A to B) corresponds to the relative homogenous core zone, referring to the area between inflexion point for 200 μm on Fig. 9a). This proves the secondary flow favours the homogenization of PCM particles. For 400 μm PCM particle, the drag force and turbulent dispersion force reduce with increasing particle size, thus the effect of secondary flow on the particle distribution is less profound.

b) $d = 70 \mu\text{m}$ f) $d = 70 \mu\text{m}$ c) $d = 200 \mu\text{m}$ g) $d = 200 \mu\text{m}$ d) $d = 400 \mu\text{m}$ h) $d = 400 \mu\text{m}$

Fig. 10. Maps of the axial velocity (left) and PCM volume fraction (right) at a) – d), and radial water velocity (left) and PCM velocity (right) at e) – h) for $U = 0.95$ m/s, $\phi_{in} = 0.2$. Diameter of PCM particle is 7, 70, 200 and 400 μm .

4.1.2. Influence of PCM concentration

To have a quantitative insight of PCM concentration on flow characteristic, Fig. 11 presents the radial normalized concentration and velocity profiles for $\phi_{in} = 0.05, 0.1, 0.2$ and 0.35 . It is clear the homogenous 70 μm slurry flow is barely affected by different concentrations, as shown in Fig. 11a) and 11b). For $d = 70$ μm and $\phi_{in} = 0.35$, a slight asymmetry on velocity profile with the maximum velocity (U_{max}) are observed. This is because small particles at higher mass loading tend to decrease the thickness of boundary layer and increase the skin friction [62], leading to an enhanced turbulence and higher U_{max} . When it comes to larger particle (400 μm), the flat normalized concentration profile of $\phi_{in} = 0.35$ indicates high PCM loading favours the uniform distribution. It can be attributed to the strong interaction forces between PCM particles to keep them stably suspended in water. For large particles, the high PCM loading also induce a steeper velocity gradient, causing a larger shear stress to repel the particles away from the top wall, resulting in a further inflexion point away from the pipe wall.

a)

b)

c)

d)

Fig. 11. Effect of inlet concentrations on PCM distribution and velocity profiles for $U_{in} = 0.95$ m/s at $x/L = 9/10$. (a) $70 \mu\text{m}$, concentration profile, (b) $70 \mu\text{m}$, velocity profile, (c) $400 \mu\text{m}$, concentration profile, (d) $400 \mu\text{m}$, velocity profile.

4.1.3. Influence of inlet velocity

Since the flow pattern of small particles ($d = 7$ and $70 \mu\text{m}$) are barely changed by varying inlet velocities ($0.05 - 4.0$ m/s), Fig. 12 shows the radial concentration and velocity profile of large ones. Increasing the inlet velocity leads to smaller concentration gradient in the pipe core, and the inflexion gradually shifts away from the upper wall with the increase of particle size. Taken $400 \mu\text{m}$ slurry as an example, the inflexion point of $U_{in} = 0.95$ m/s decreases from $y/D = 0.33$ to $y/D = 0.17$ for $U_{in} = 4.0$ m/s. For $d = 200 \mu\text{m}$, the regime of uniform fluid core decreases with increasing inlet velocity, occupies 0.812 of the vertical radius for $U_{in} = 0.95$ m/s but decreases to 0.732 for $U_{in} = 4.0$ m/s. This is because the steep velocity gradient of high velocity ($U_{in} = 4.0$ m/s), as shown in Fig. 12 c), repels the particles away from upper and bottom wall.

a)

b)

c)

Fig. 12. Effect of inlet velocities on PCM distribution and velocity profiles for $\phi_{in} = 0.2$ at $x/L = 9/10$. (a) 400 μm , concentration profile, (b) 200 μm , concentration profile, (c) 200 μm , velocity profile.

The effect of inlet velocities can be further studied via visualization of the fully developed radial flow, as shown in Fig. 13. On Fig. 13a) and 13b), increasing inlet velocity favours the growth of PCM velocity and clusterization of PCM in pipe core. The distinguished inflexion points A' and B' on Fig. 13b) locates exactly on the edge of main secondary vortices, where a circular ring of the high concentration can be spotted. The streamlines indicate the accumulated particles are transported from both the secondary flow and outer boundary layers. The turbulence kinetic energy k is found to increases with increasing inlet velocity, but the radial velocity field is not sensitive to the inlet velocity.

Fig. 13. Effect of inlet velocities ($U_{in} = 0.05$ and 4.0 m/s) on radial flow pattern for $d = 200$ μm and $\phi_{in} = 0.2$ at $x/L = 9/10$. The left and right contour of a) and b) refers to PCM velocity and PCM volume fraction, respectively, and the left and right contour of c) and d) is the turbulence kinetic energy and water velocity, respectively.

4.2. Friction factor correlations

The phase change process is considered when calculating the overall pressure drop, which is expressed in terms of Darcy friction factor and given as:

$$f = \frac{D\Delta P}{L} \cdot \frac{2}{\rho_m U_m^2} \quad (6)$$

where ρ_m is the mixture density. The present simulation are carried out with a constant wall heat flux of $Q = 80000$ W/m^2 and temperature-sensitive properties from the measurement. Fig. 14 compares the friction factor from present simulation (Euler-Euler and homogenous model) and modified literature correlations for $U_{in} = 0.5 - 4.0$ m/s, $\phi_{in} = 0.05 - 0.35$ and $d = 7 - 400$ μm . It is noteworthy that the coefficients of the Blasius and Reghem correlation for turbulent flow are adjusted, as given by:

Modified Blasius [63] correlation:

$$f = 0.301 \text{Re}^{-0.25} \quad (7)$$

Classical Prandtl-Karman-Nikuradse (PKN) correlation[64]:

$$f = \left[0.8686 \ln \left(\frac{\text{Re}}{1.964 \ln \text{Re} - 3.8215} \right) \right]^{-2} \quad (8)$$

Modified Reghem [65] correlation:

$$f = f_l + 3580\phi^{2.73}f_l^{1.742}F_*^{-0.767} \quad (9)$$

where f_L is the friction coefficient for pure water under the same conditions and $F_* = \frac{U_{in}^2}{Dg(1-\rho_s/\rho_l)}$ refers to the Froude number. For homogenous model, the viscosity of pure water under the same condition is used for Reynolds number calculation. The friction factor of homogenous model is higher than that of Euler-Euler model by 20.6 % in average. For Euler-Euler model, the Re number of a given inlet velocity oscillates between 1.4% and 5.2% due to different viscosities and densities under various ϕ_{in} and d . Increasing the PCM concentration ($\phi_{in} = 0.05 - 0.35$) or decreasing particle diameter ($d = 7 - 400 \mu m$) would lead to a higher average friction factor by 10.4 % and 11.7 %, respectively. Understandingly, the growth of PCM concentration favours the increase of fluid viscosity and skin friction. The small particles tend to decrease the thickness of boundary layer thus increase the friction factor. The pressure drop measurement from Wang et al. [40] confirms the application of Blasius equation in slurry flow. The present modified Blasius correlation shows best agreement with calculated value with average deviation of 2.93 %, but both Blasius and PKN correlations ignore the effect of concentration and particle size on friction factor. The semi-empirical Reghem correlation fits for $\phi_{in} \leq 0.3$ and $0.1 \text{ m/s} \leq U_{in} \leq 3 \text{ m/s}$, which is close to the current work. The modified Reghem correlation includes both the temperature-sensitive density and PCM concentration, with average deviation of 7.59%, thus Eq (9) is recommended for PCD pressure prediction.

Fig. 14. Friction factor of turbulent PCD from present simulation (Euler-Euler and homogenous model), modified literature correlations for $U_{in} = 0.5 - 4.0 \text{ m/s}$, $\phi_{in} = 0.05 - 0.35$ and $d = 7 - 400 \mu m$.

4.3. Heat transfer correlations

Fig. 15 compares the wall and bulk temperature of homogenous model and Euler-Euler model along the pipe length of $L = 5.5$ m. It is clear that the homogenous model underpredicts the wall temperature, because it fails to catch the unevenly distributed particle near the pipe wall. The bulk temperature is less sensitive to the calculation models. On Fig. 15, the bulk temperature of homogenous model and Euler-Euler model at $d = 7 \mu\text{m}$ are almost identical, because of the evenly distributed small particles. At the latter half pipe, a temperature increment of up to 0.11 K from 200 μm Euler-Euler calculation can be spotted.

For Euler-Euler model, the higher wall temperature can be found at large particle size. A noteworthy fact is the top wall temperature is significantly higher than bottom one for large particles, reaching the temperature difference between 3.02 K (for 70 μm) and 11.3 K (for 200 μm). This is attributed to the low efficient thermal conductivity caused by higher PCM concentration at the upper half of the pipe. The wall difference reaches up to 35.7% of the inlet and outlet temperature difference, resulting in large deviations for Nusselt number calculation. Thus in the study of PCD heat transfer, it is recommended the wall temperature should be measured and averaged along the perimeter for a certain pipe length.

Fig. 15. Wall (top and bottom) and bulk temperature along the pipe length for homogenous model and Euler-Euler (E-E) model of 7 μm and 200 μm , $U_{in} = 0.95$ m/s, $\phi_{in} = 0.2$.

The effects of particle diameters, velocities and PCM concentrations on overall heat transfer are presented in Fig. 16. The Nusselt number is defined as $Nu = \frac{Q}{T_w - T_b} \cdot \frac{D}{k_f}$, and the average Nusselt number is calculated using the arithmetic averages of the local values. To accurately describe the wall temperature, the mean value of the top and bottom wall is used for Nu calculation. The discrepancy of Nu number caused by wall temperature difference can reach

up to 47.03% at $d = 400 \mu\text{m}$. On Fig. 16a), the Nusselt number of homogenous model is significantly higher than the two-phase model due to the inaccurate wall temperature prediction. The phase change regime can be easily detected for small particle size at $x/D = 20 - 150$. The heat transfer decreases with increasing diameter, and it may be lower than water due to low efficient thermal conductivity. Nevertheless, the cooling performance can be enhanced by increasing velocities and higher PCM concentrations. As shown in inset of Fig. 16b), increasing velocities 8 times ($0.5 - 4 \text{ m/s}$) results in the growth of averaged Nu number by 7.37 times. The heat transfer performance is less sensitive to the PCM concentration variation, because its effect on effective thermal conductivity is small. However, high ϕ_{in} will decrease the bulk temperature as given in the inset of Fig. 16c).

a)

Fig. 16. Variation of Nusselt number along the pipe length of a) particle size, b) velocity and c) PCM concentration on Nusselt number.

The majority of Nusselt number correlations were developed based on isothermal condition. To include the effect of phase change, the coefficients of classic Nu correlations for turbulent flow are modified using the least square regression analysis of current calculation, and summarized in Table 4. Also shown in Fig. 17 are plots of the modified correlations as given in the Table. The correlations proposed by Salamone and Newman [66] and Özbelge and Somer [67] show poor agreement at larger Nu number, because the D/d_p working limit of their model is small compared to the present one ($35 \leq D/d_p \leq 2000$). Predictions from Gnielinski [68] and Harada et al. [69] fails to follow the Nu growth because the present Re number ($16771 \leq Re \leq 90596$) exceeds their scope of application ($8000 \leq Re \leq 50,000$). The model proposed by Churchill [70] is validate to fully developed flow in smooth tubes for a wide Reynolds number ($Re > 2100$). It succeeds in following the growth trend especially at high Nu number with average deviation of 17.78%. The Choi and Cho [71] model provides satisfactory prediction at low Nu but under-predictes the results by 18.41% with the growth of high Nu number. The modified model of Wang et al. [72] considers the Re, Pr, Ste and phase change region length, and it shows best agreement with the calculated value with deviation less than 5.62%. Ho et al. [41]'s model is validated at low Reynolds number and show large deviations up to 78.45%, thus not presented in the figure. As a results, the modified Nu correlation (Eq. (16)) based on Wang et al. [72] is recommended slurry heat transfer study, validated for $35 \leq D/d_p \leq 2000$, $16771 \leq Re \leq 90596$ and $3.4 \leq Pr \leq 8.7$.

Fig. 17. Comparison of calculated Nusselt number (from Euler-Euler model) against the predicted value from modified correlations.

4.4. Energy transport characteristics of PCD

The PCD heat transfer enhancement is associated with the increase in pressure drop. To evaluate the overall performance, an energetic performance evaluation criterion (PEC) is introduced, which is defined as ratio of heat transfer and hydrodynamics and given by:

$$PEC = \frac{Nu_{PCD}/Nu_w}{(f_{PCD}/f_w)^{1/3}} \quad (18)$$

The overall performance of PCD is better than water when PEC higher than 1. On Fig. 18, the lowest PEC can be spotted at $d = 400 \mu\text{m}$ PCD, which is only half of the water under the same condition. Decreasing particle size to $7 \mu\text{m}$ results in a comparable PCD performance of water at the low velocity $U = 0.95 \text{ m/s}$. Nevertheless, the PEC can be increased at high inlet velocity and PCM concentration. The thermal performance can be enhanced to 1.35 times of water at $\phi_{in} = 0.35$ and $U_{in} = 4 \text{ m/s}$. Therefore, the developed fatty acid PCD of $d = 7 \mu\text{m}$ operating at high velocity and PCM concentration is recommended for high voltage electrical converter cooling.

Fig. 18. Influence of parameters on performance evaluation criterion. $U_{in} = 0.5 - 4$ m/s, $\phi_{in} = 0.05 - 0.35$, $d = 7 - 400$ μm .

5. Conclusions

In this work, the developed fatty acid-based PCD for efficient high voltage electrical devices cooling was characterized and studied in a circular pipe both experimentally and numerically. Such PCD was designed to have low electrical conductivity to ensure applicability in the high voltage environment and also doubled heat capacity over water during the melting temperature range of 47.5-50 °C. Experiments were firstly carried out to measure the properties of the formulated PCD by different facilities and to detect the bulk and wall temperatures of the turbulent PCD flow in a circular pipe by a self-designed rig. A 3D numerical model based on the Euler-Euler model and single-phase homogenous model was then established to evaluate the thermal characteristics of the PCD. The following conclusions are drawn from this study:

- 1) The Herschel-Bulkley model was able to accurately describe the non-Newtonian rheology behaviour with an average deviation of 10.19% between the modelling results and experimental data observed. Compared to Euler-Euler model, the homogenous model did not capture the thin layer of small particle accumulation in viscous sub-layer, and hence under-predicted the wall temperature, leading to large deviation of heat transfer calculation.
- 2) The flow characteristic had a significant effect on thermal performance of the PCD. The PCM particles larger than 200 μm showed the tendency to float upwards, which reduced the effective thermal conductivity at the upper half. Therefore, the top wall temperature was significantly higher than the bottom wall, which may occupy up to 35.7% of the inlet and outlet difference. As a result, the wall temperature should be

averaged along the perimeter at a certain length, especially for PCD flow with large particles.

- 3) Due to the increased viscosity and decreased boundary layer thickness, increasing the PCM concentration from 0.05 to 0.35 and decreasing particle diameter from 7 μm to 400 μm led to an increase of average friction factor by 10.4% and 11.7%, respectively.
- 4) The higher averaged Nusselt number and larger pressure drop appeared when the PCM particle diameter decreases to 7 μm . The modified Reghem correlation considering both the temperature –sensitive density and PCM concentration, with an average deviation of 7.59%, was recommended for PCD pressure prediction.
- 5) The heat transfer coefficient increased dramatically with inlet velocity but slight with the growth of concentration. The modified Nu correlation based on Wang et al. [72] is recommended for PCD heat transfer study, validated at $35 \leq D/d_p \leq 2000$, $16771 \leq Re \leq 90596$ and $3.4 \leq Pr \leq 8.7$ with average deviation of 5.62%.
- 6) For the given operating conditions in this work, an optimal set of cooling performance for the developed fatty acid PCD was proposed and a PCM particle size of 7 μm with a flow velocity of 4 m/s and a concentration of 35% was recommended for high voltage electrical converter cooling.

Table 4. Modified correlations of Nusselt number for turbulent flow.

Source	Equation	Working conditions	Eq. No
Salamone and Newman [66]	$Nu = 0.094Re^{0.62}Pr^{0.72}\left(\frac{k_p}{k_f}\right)^{0.05}\left(\frac{D}{d_p}\right)^{0.05}\left(\frac{C_{p,p}}{C_{p,f}}\right)^{0.35}$	$14,000 \leq Re \leq 140,000$ $3.4 \leq Pr \leq 12.7$ $2.3 \% \leq w_p \leq 10.7 \%$ $282 \leq D/d_p \leq 10,500$ $0.09 \leq C_{p,p}/C_{p,f} \leq 0.22$	(10)
Gnielinski [68]	$Nu = \frac{1.326(\varepsilon/8)(Re_D - 1000)Pr}{1 + 12.7(\varepsilon/8)^{0.5}(Pr^{2/3} - 1)}$ $\varepsilon = (1.82 \log_{10} Re_D - 1.64)^{-2}$	$2300 \leq Re \leq 50,000$	(11)
Churchill [70]	$Nu = 23.96 + \frac{0.329PrRe\left[\left((8/Re)^{10}(Re/36500)^{20}\right)^{-1/2} + \left(2.21 \log \frac{Re}{7}\right)^{10}\right]^{-1/10}}{(1 + Pr^{4/5})^{5/6}}$	$Re > 2100$ $0.1 \leq Pr \leq 1000$	(12)
Harada et al. [69]	$Nu = 0.0156Re^{0.88}Pr^{1/3}\left(\frac{\mu_f}{\mu_w}\right)^{0.14}$	$8000 \leq Re \leq 50,000$ $0.0024 \leq d/D \leq 0.071$	(13)
Özbelge and Somer [67]	$Nu = 0.113Re^{0.6}Pr^{0.675}\left(\frac{D}{d_p}\right)^{0.092}\left(\frac{\mu_f}{\mu_w}\right)^{-1.95}$	$27,000 \leq Re \leq 120,000$ $1.17 \leq \mu_p/\mu_f \leq 1.83$ $282 \leq D/d_p \leq 512$ $0.5 \% \leq w_p \leq 3 \%$	(14)
Choi and Cho [71]	$Nu = 0.0051Re_{lb}^{0.979}Pr_{lb}^{0.4}(\mu_{lw}/\mu_{lb})^{-0.11}$	Single turbulent flow	(15)
Wang et al. [72]	$Nu = 6.79 \times 10^{-4}Re_m^{1.2733}Pr_m^{1.251}Ste^{0.3159} \times [(L_1 + L_2)/D]^{-0.85}(\mu_m/\mu_w)^{-0.43}$	$2100 \leq Re_m \leq 3500$ $13 \leq Pr_m \leq 15$ $5\% \leq w_p \leq 10\%$	(16)
Ho et al. [41]	$Nu = a\left(\frac{Pe}{L/D_h}\right)^b\left(1 + \frac{c_m}{Ste(1+Sb)}\right)$ $Sb = (T_m - T_{in})/\Delta T_{ref}$	$665 \leq Pe \leq 7550$ $133 \leq Re_m \leq 1515$ $0\% \leq w_p \leq 10\%$	(17)

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Nomenclature	
C_p	specific heat capacity, (kJ/kg·K)
d	droplet diameter, (m)
D	pipe diameter, (m)
e_{ss}	particle-particle restitution coefficient
f	friction coefficient
F^*	Froude number
h	latent heat, (kJ/kg)
k	thermal conductivity, (W/m·K)
L	length, (m)
$\dot{m}$	mass flow rate, (kg/s)
Nu	Nusselt number
P	pressure, (Pa)
P_{el}	electrical power (W)
Pr	Prandtl number
Q	heat flux (W/m ²)
R	correlation coefficient
R_b	interfacial thermal resistance, (m ² ·K/W)
Re	Reynolds number
Ste	Stefan number
t	time, (s)
T	temperature, (°C)
$\vec{v}$	velocity vector, (m/s)
U	average velocity, (m/s)

Y_d	cumulative volume fraction
<i>Greek symbols</i>	
α	Biot number
γ	shear rate, (Pa)
μ	dynamic viscosity, (kg/(m·s))
ρ	density, (kg/m ³)
ϕ	PCM concentration, (%)
<i>Subscripts</i>	
HVDC	high voltage direct current
L	liquid phase
m	mixture
P, PCM	phase change material
PCD	phase change dispersion
s	solid phase

Appendix

Table A1. Mathematical equations of Euler-Euler model

Description	Equation	Ref	Eq. No
Continuity equation	$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i) = 0$	-	(A1)
Momentum equation	$\frac{\partial}{\partial t}(\alpha_i \rho_i \vec{v}_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i \vec{v}_i) = -\alpha_i \nabla P + \nabla \cdot \bar{\tau}_i + \alpha_i \rho_i \vec{g} + \vec{F}_D + \vec{F}_L + \vec{F}_{td} + \vec{F}_{VM}$	-	(A2)
	$\bar{\tau}_i = \alpha_i \mu_i \left[\nabla \vec{v}_i + (\nabla \vec{v}_i)^T - \left(\frac{\zeta_i}{\mu_i} - \frac{2}{3} \right) \nabla \cdot \vec{v}_i \vec{I} \right]$		
k- ω SST turbulence kinetic energy	$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(v + \alpha_k v_T) \frac{\partial k}{\partial x_j} \right]$	[73]	(A3)
k- ω SST specific dissipation rate	$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(v + \alpha_k v_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}$	[73]	(A4)
Granular temperature	$\frac{3}{2} \left[\frac{\partial}{\partial t} (\alpha_s \rho_s \theta_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s \theta_s) \right] = (\bar{\tau}_s - P_s \vec{I}) \cdot \nabla \vec{v}_s + \nabla \cdot (k_{\theta_s} \nabla \theta_s) + \varphi_{sl} - \gamma_{\theta_s}$	[74]	(A5)
Shear viscosity of solid phase	$\mu_s = \frac{4\alpha_s \rho_s d(1 + e_{ss})g_0 \sqrt{\theta_s}}{5\sqrt{\pi}} + \frac{10\rho_s d \sqrt{\pi \theta_s}}{96\alpha_s(1 + e_{ss})g_0} \left[1 + \frac{4(1 + e_{ss})g_0 \alpha_s}{5} \right]^2$	[51]	(A6)
Bulk viscosity of solid phase	$\zeta_s = \frac{4\alpha_s \rho_s d g_0 (1 + e_{ss}) \sqrt{\theta_s}}{3\sqrt{\pi}}$	[75]	(A7)
Radial distribution function	$g_0 = \left[1 - (\alpha_s / \alpha_{s,max})^{1/3} \right]^{-1}$	[76]	(A8)
Solid phase pressure	$P_s = \alpha_s \rho_s \theta_s [1 + 2g_0 \alpha_s (1 + e_{ss})]$	[77]	(A9)
Drag force of liquid phase	$\vec{F}_{D,l} = \frac{C_D Re_s \alpha_l}{24 v_{r,s}^2}$ $C_D = \left(0.63 + \frac{4.8}{\sqrt{Re_s / v_{r,s}}} \right)^2$	[51]	(A10)

Lift force	$F_{L,l} = \frac{2C_L v^{0.5} \rho d_{ij}}{\rho_s d (d_{lk} d_{kl})^{0.25}} \vec{v}_s - \vec{v}_l $	[52]	(A11)
Turbulent dispersion force	$F_{td,1} = C_{td} \gamma_{sl} \frac{\mu_{t,1}}{\sigma_{sl}} \left(\frac{\nabla \alpha_s}{\alpha_s} - \frac{\nabla \alpha_l}{\alpha_l} \right)$	[53]	(A12)
Energy equation	$\frac{\partial}{\partial t} (\alpha_i \rho_i H_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i H_i) = \nabla \cdot (\lambda_{e,i} \nabla T_i) + \bar{\tau}_i \cdot \vec{v}_i - h_{sl} (T_i - T_q)$	-	(A13)
Volumetric heat transfer coefficient	$h_{sl} = \frac{6\alpha_s \lambda_l}{d^2} \left[(7 + 10\alpha_l + 5\alpha_l^2)(1 + 0.7Re_s^{0.2} Pr^{1/3}) + (1.33 - 2.4\alpha_l + 1.2\alpha_l^2) Re_s^{0.7} Pr^{1/3} \right]$	[54]	(A14)
Effective thermal conductivity in near wall region	$\lambda_{e,l} = \alpha_l \lambda_l (L/d_s < 0.5), \lambda_{e,s} = 3\alpha_s \lambda_l SC (L/d_s < 0.5). S = 2L/d$	[78]	(A15)
Effective thermal conductivity in main flow region	$C = \left(\frac{A}{A-1} \right)^2 \left[\left(1 - \frac{1-S}{A} \right) \ln(A) - \frac{A-1}{A} S \right]$ $A = k_l / k_s$ $k_{e,l} = (1 - \sqrt{\alpha_s}) k_l$ $k_{e,s} = \sqrt{k_s} (\beta A + (1 - \beta) K) \lambda_l$ $K = \frac{2}{1 - \frac{B}{A}} \left[\frac{A-1}{\left(1 - \frac{B}{A}\right)^2} \frac{B}{A} \ln \frac{A}{B} - \frac{B-1}{1 - \frac{B}{A}} - 0.5(B+1) \right]$ $B = 1.25(\alpha_s / \alpha_l)^{10/9}$	[79]	(A16)
Johnson-Jackson shear force	$\tau_{sw} = - \frac{\sqrt{3} \rho_s g_0 \alpha_s \varphi \sqrt{\theta_s} \vec{v}_{sw}}{6\alpha_{s,max}}$	[80]	(A17)
Johnson-Jackson fluctuating energy	$q_{sw} = \frac{\sqrt{3} \rho_s g_0 \alpha_s \varphi \sqrt{\theta_s} \vec{v}_{sw} \vec{v}_{sw}}{6\alpha_{s,max}} - \frac{\sqrt{3} \rho_s g_0 \alpha_s \varphi (1 - e_{sw}^2) \theta_s^{3/2}}{4\alpha_{s,max}}$	[80]	(A18)

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Highlights

- Dielectric phase change dispersion designed for HVDC converter cooling developed
- 3D modelling based on Euler-Euler and homogenous models performed and compared
- Improved pressure drop and heat transfer correlations of PCD proposed
- The importance of averaging wall temperature along perimeter addressed
- Optimal PCD cooling condition based on overall performance evaluation given

Dear Editor-in-Chief,

We would like to submit the enclosed manuscript entitled "Experimental and numerical studies of a fatty acid based phase change dispersion for high voltage electrical devices cooling enhancement", which we wish to be considered for publication in *Energy*. We declare that we do not have any commercial or associate interest that represents a conflict of interest in connection with the work submitted.

If you have any queries, please do not hesitate to contact me at the address below.

Thank you very much for your time and consideration.

Kind Regards,

Yours sincerely,

Qi Li & Chuan Li & Yulong Ding

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