Computational Fluid Dynamics Study of Turbulence Effects in Heat Pipe Heat Exchangers for Power-Cell Micro-Reactors

Katlego Pule[1]**, Emmanuel Igumbor**[1]**, Mbolahasina Ralijaona**[1]**, Simon Connell**[1]**, and Johan Slabber**[2]

[1]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa

[2]Mechanical Engineering, University of Pretoria, Lynnwood Road, Hatfield, 0028, Pretoria, South Africa

E-mail: katlegopule59@gmail.com

Abstract. The increasing demand for efficient thermal management systems in micro-reactors has underscored the importance of heat pipe heat exchangers (HPHEs). Heat, when extracted from the reactor, is conveyed to the working fluid, which, if not isolated, can lead to the distribution of contaminants in the secondary cycle. This contaminant can lead to environmental degradation through oxidation, carburization, or decarburization of alloys. Specifically, the HPHE could be used to eliminate tritium contamination from entering the secondary cycle through heat transfer management. In this study, we first develop a simulation model and then investigate the effect of different turbulence models on a newly designed HPHE, using computational fluid dynamics (CFD). Two turbulence models, K-epsilon (k-ϵ) and the Large Eddy Simulation (LES), were investigated. Helium and air were used as hot and cold fluids, respectively. A Lead-Bismuth eutectic was used as an intermediate fluid within the heat pipes. The LES result showed a reduction in helium temperature from $1023\,\mathrm{K}$ to $500\,\mathrm{K}$ and a corresponding increase in that of the air from $403\,\mathrm{K}$ to $722\,\mathrm{K}$. The k-ϵ model, on the other hand, shows a significant heat reduction acting on helium from $1023\,\mathrm{K}$ to $723\,\mathrm{K}$. The air temperature has increased from $403\,\mathrm{K}$ to $722\,\mathrm{K}$. In contrast to the k-ϵ, the LES turbulence model improves more the heat control performance of the HPHE. In all, this study demonstrates that the designed HPHE can be effectively used to control temperature and mitigate the formation of contaminants in a micro-reactor. Subsequent research will focus on improving heat extraction and optimizing the HPHE to achieve reduced helium temperatures.

1 Introduction

Heat pipe heat exchanger (HPHE) technology is used to dissipate excess heat generated by refrigerators, air conditioners, and greenhouses [1], among others. This is common in industrial applications, data centers, and power plants, where efficient cooling and heat control are needed to prevent overheating [2]. In a nuclear micro-reactor, the HPHE plays a crucial role, contributing to the safe and efficient cooling of its operational systems [1]. In a micro-reactor, the HPHE systems are used to facilitate the transfer of heat from the primary coolant loop to the secondary cooling loop. The primary coolant loop circulates the coolant through the reactor core and absorbs the thermal energy from the nuclear fission process [3]. The secondary cooling loop accepts heat via the primary cooling loop through the intermediate working fluid. Finally the heat is used to produce steam to drive turbines and generate electricity [3]. The efficiency of a micro-reactor is closely linked to the performance of the HPHE systems [3]. The heat exchange process directly influences the thermal efficiency of the micro-reactor. The HPHE is used to manage and dissipate heat during abnormal or emergency conditions, such as a cooling loss accident or a shutdown of the reactor [4]. Therefore, maximizing the thermal efficiency of the micro-reactor, results in increased electricity generation [5].

Depending on the temperature range and application, HPHEs use a variety of working fluids, however, in the event of a leak or system failure, some of these fluids may present contamination risks [6]. When selecting fluids, thermodynamic efficiency and environmental effects must be considered [7]. Ammonia has been widely used for heating and cooling, especially when high thermal power is required [7]. However, when released into the atmosphere, ammonia poses serious health and environmental hazards due to its extreme toxicity and corrosiveness [7]. Ethanol and methanol are frequently utilized in low-temperature applications; nonetheless, they are both poisonous and combustible, with methanol posing significant hazards when inhaled or applied to the skin [8]. Helium is also used in a micro-reactor. In a micro-reactor, the impurities generated in the helium fluid can lead to environmental degradation of high-temperature alloys used in reactor internals [9]. These impurities, which may include water vapor and carbon compounds, can cause oxidation, carburization, or decarburization of the alloys [9]. Therefore, there is a need to control the heat in a micro-reactor using an intermediate heat exchanger. The heat exchanger can be deployed to eliminate the tritium contamination from entering the secondary cycle [10].

Computational Fluid Dynamics (CFD) is an engineering tool used for modeling complex systems across a range of disciplines [11]. Numerous studies have utilized CFD to investigate fluid flow behavior, thermal management, velocity profiles, relative humidity, and heat transfer in various engineering applications [12]. More recently, CFD has been employed to analyze thermal performance and flow behavior in heat exchangers [13]. Also, a CFD study on microchannel heat sinks for electronic cooling, focusing on different hydraulic diameters, surface area, and channel count using water under steady-state conditions with a constant heat flux and mass flow rate has been reported [14]. Increasing the number of channels and hydraulic diameter significantly reduced surface temperatures [14]. To enhance heat transfer in a concentric tube heat exchanger when equipped with trapezoidal vortex generators (VGs), a CFD study was deployed [15]. The study revealed that all configurations with VGs showed elevated thermal performance compared to the baseline [15]. For instance, placing VGs inside the tube produce the highest improvements in heat transfer ratios and thermal enhancement factors [15].

South Africa has been experiencing shortage of power supply and drastic effort must be taken to address this problem. Recently, a new micro-reactor design has been called for in South Africa to enhance power generation. However, before the micro-reactor can function efficiently, it is essential to control its heat performance. Therefore, a new HPHE must be designed to ensure efficient heat management. To facilitate this design, CFD simulation must be conducted to provide valuable insights into the performance of the newly designed HPHE. However, no studies have yet been carried out on this newly designed HPHE. Therefore, it becomes necessary to deploy the CFD simulation method to investigate the thermal behavior of HPHE. Various turbulence models, such as the k-epsilon, k-omega, Reynolds Stress Model, and Large Eddy Simulation (LES), are implemented in CFD. We intend to trial some selected turbulence models to determine which is most suitable for efficient heat management in the newly designed HPHE. In this study, helium was used as a hot fluid, and air as a cold fluid. A lead bismuth eutectic (LBE) was used as an intermediate working fluid.

2 Methodology

CFD was used to model a simplified geometry of the HPHE. The HPHE consists of two sets of pipes conjoined at their own plenums and immersed in a working fluid, LBE, similar to reference [16]. LBE has melting and boiling points of $396\,\mathrm{K}$ and $1943\,\mathrm{K}$ [17], respectively. Since the LBE alloy has substantially higher boiling points, operating a reactor with LBE coolant at much higher temperatures is not a risk [16]. It also serves as an excellent radiation shield, absorbing gamma radiation, and does not readily react with water, air, or helium to form contaminants that can cause harm to the performance of a typical micro-reactor [17]. In this study, while the inlet temperature of the helium fluid was set to $1023\,\mathrm{K}$, that of the air was set to $403\,\mathrm{K}$. 1.

The HPHE involves two primary physical phenomena: fluid flow and heat transfer. Helium flows from one end of the pipes, transferring heat to the surrounding LBE. The LBE, on the other hand, flows around the helium and air pipes and within an enclosure box while transferring heat from the helium to the air pipe. Finally, the air flows inside its designated pipe from one end and receives the transferred heat. This interplay of fluid flow and heat transfer in an HPHE is essential for thermal management of a micro-reactor. In this study, we used commercially available software (Ansys Fluent 2024 R2 version) [18] for all CFD simulations.

In CFD, the mathematical formulation must be well-defined to accurately account for the physics of the modeled system. The CFD solves the Navier-Stoke's equations of momentum, continuity, and energy. The governing equations of the Navier-Stokes are listed in Table 1. In this study, we focused on only two turbulence models (the $k-\epsilon$ model and LES). Furthermore, we also consider the effect of buoyancy in the turbulent flow by applying the Boussinesq approximation. In the governing equations, $\vec{u}$ represents the velocity vector, p is the static pressure, and

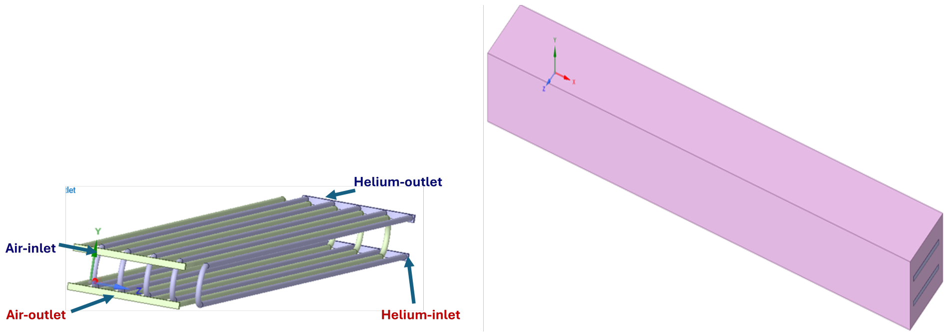

Figure 1: *left* The geometry structures of the HPHE. The air inlet is located at the top, and the Helium inlet is located at the bottom. Air plenums and pipes are green, and Helium plenums and pipes are blue. The air inlet plenum is located at the top as air flows into the chambers and then exits from the outlet, which is located at the bottom of the HPHE. Helium inlet is seen on the other side of the HPHE at the bottom, and it flows from the bottom up through the chambers of the Helium pipes. *right* The LBE enclosure box. LBE is injected into the enclosure box.

ρ is the fluid density. The dynamic viscosity is denoted by μ, while μ_t is the turbulent (eddy) viscosity. Temperature is expressed as T, and c_p is the specific heat capacity at constant pressure. The turbulent kinetic energy is given by k, and its dissipation rate by ϵ. The term P_k refers to the production of turbulent kinetic energy. Buoyancy effects are included via the buoyancy force vector $\vec{F}_b = \rho\vec{g}\beta(T - T_{\text{ref}})$, where $\vec{g}$ is gravitational acceleration, β is the thermal expansion coefficient, and T_{ref} is a reference temperature. The term Φ represents viscous dissipation in the energy equation. In the LES turbulence, quantities with a bar represent filtered values of the quantities; $\overline{u_i u_j}$ is a filtered product of velocity components u_i, u_j, and τ_{ij} is the sub-grid scale (SGS) stress tensor. The SGS turbulent viscosity ν_t is modeled using the Smagorinsky model $\nu_t = (C_s\Delta)^2|\bar{S}|$, where C_s is the Smagorinsky constant, Δ is the filter width, and $\bar{S}$ is the strain rate magnitude.

Table 1: The Navier-Stokes equations of momentum, continuity, energy, and the turbulence equations.

Continuity	$\nabla \cdot \vec{u} = 0$
Momentum	$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \vec{F}_b + \vec{F}_t$
Energy	$\rho c_p\left(\frac{\partial T}{\partial t} + \vec{u}\cdot\nabla T\right) = \nabla\cdot(k\nabla T)$
Buoyancy Boussinesq approximation	$\vec{F}_b = \rho\vec{g}\beta(T - T_{\text{ref}})$
k Equation	$\frac{\partial(\rho k)}{\partial t} + \nabla\cdot(\rho k\vec{u}) = \nabla\cdot\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right) + P_k - \rho\epsilon$
ϵ Equation	$\frac{\partial(\rho\epsilon)}{\partial t} + \nabla\cdot(\rho\epsilon\vec{u}) = \nabla\cdot\left(\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\nabla\epsilon\right) + C_{1\epsilon}\frac{\epsilon}{k}P_k - C_{2\epsilon}\rho\frac{\epsilon^2}{k}$
Turbulent Viscosity	$\mu_t = C_\mu\frac{\rho k^2}{\epsilon}$
LES Momentum	$\frac{\partial\bar{u}_i}{\partial t} + \bar{u}_j\frac{\partial\bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial\bar{p}}{\partial x_i} + \nu\frac{\partial^2\bar{u}_i}{\partial x_j^2} - \frac{\partial\tau_{ij}}{\partial x_j}$
SGS Stress (LES)	$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i\bar{u}_j, \quad \nu_t = (C_s\Delta)^2\lvert\bar{S}\rvert$

Boundary conditions (BC) corresponding to the inlet operational conditions are employed in the CFD simulations. The BC supplemented by auxiliary conditions is used to specify how the fluid behaves against solid walls, inlets, and interfaces, as well as provide control over the simulations. The outlet temperatures are determined by the simulation. The BC parameters, are listed in Table 2. The inlets were configured as mass flow inlets, while the outlets were set as pressure outlets at atmospheric pressure levels. The "no-slip" condition was applied to the walls. Convection is imposed at the pipes boundaries to correctly capture heat transfer between the helium and air pipe, through the working fluid. The heat transfer coefficient (h) for helium and air as listed in Table 2, are 1790 W/m^{2}K and 264.00 W/m^{2}K, respectively.

Table 2: Boundary conditions applied to Helium-air HPHE for flow and thermal analysis

Boundary	Flow conditions	Thermal
Helium inlet	Mass flow of 0.035 kg/s	1023 K
Helium outlet	Atmospheric pressure	Backflow 1023 K
Air inlet	Mass flow of 0.14 kg/s	403 K
Air outlet	Atmospheric pressure	Backflow 1023 K
Helium pipe	No slip condition	Convection ($h = 1790\ \mathrm{W/(m^2 \cdot K)}$)
Air pipe	No slip condition	Convection ($h = 264\ \mathrm{W/(m^2 \cdot K)}$)
HPHE box	No slip condition	Zero heat flux

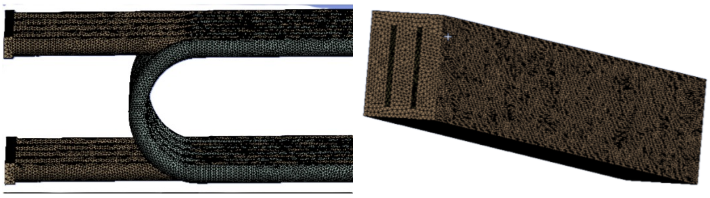

Figure 2: *left* Air and helium pipes meshed. Side view. *right* The LBE enclosure box meshed

The HPHE geometry was carefully meshed, leading to a total of 25 million cells. The mesh was finer around the pipes to accurately capture the heat transfer occurring in those regions. Figure 2 displays the mesh around the pipes. To obtain a more robust implementation of steady-state flow, we used the coupled pressure-velocity coupling scheme [19]. The coupled pressure-velocity coupling scheme combines the continuity and momentum equations to calculate the pressure in a pressure-based solver. Simulations were done using the finite volume method with under-relaxation of variables and second-order spatial and temporal discretization. Gradients were discretized using a cell-based least-squares method [18].

3 Results and Discussion

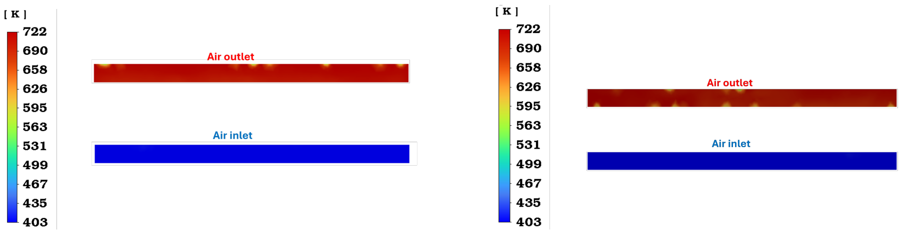

Figure 3: The temperature profiles of the air flow in the HPHE; *left* k-ϵ model and *right* LES model

Figure 3 displays the image of the temperature profile of cool air in the HPHE. Using the k-ϵ model we observed that the outlet temperature of air reaches 722 K. In the air pipe there was a smooth, layered profile, which suggests a relatively uniform heat transfer from the hot region. However, the bulk convection primarily governs the flow, with minimal impact from turbulent mixing. Also for the LES model (right), we observed an outlet temperature increase to 722 K, exhibiting greater temperature variation and noticeable fluctuations in the contours across the outlet. This shows the existence of eddies and turbulent structures captured by the LES model, resulting in improved mixing and a more accurate prediction of flow behavior. The k-ϵ and LES models yielded a comparable outlet temperature, however, the LES offers a more comprehensive understanding of flow instabilities and spatial temperature gradients.

Figure 4 displays the image of the temperature profile of hot fluid in the HPHE. The k-ϵ model shows that the outlet temperature decreases from 1023 K to approximately 723 K, reflecting a cooling effect of 300 K. The contours exhibit increased smoothness and suggest more predictable flow patterns. However, the flow provide less detail on localized phenomena. Conversely, the LES model showed a significantly greater cooling effect, with the helium outlet temperature decreasing to as low as 500 K. The outlet contours exhibit increased turbulence-induced

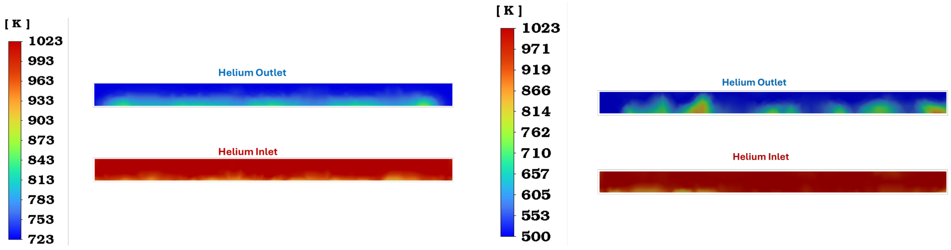

Figure 4: The hot fluid (helium) temperature profile of the HPHE. *Left* k-ϵ model, and *Right* LES model.

irregularities, facilitating localized mixing that improves heat transfer. In contrast to the k-ϵ, the LES turbulent model provides more superior cooling performance by capturing transient and unsteady flow characteristics.

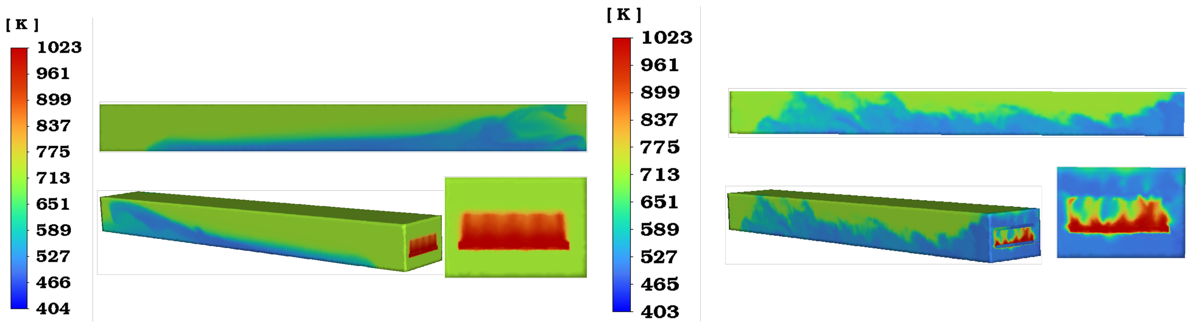

Figure 5: *left* k-ϵ LBE enclosure box. Bottom right shows the front view of the helium inlet. *right* LES LBE enclosure box. Bottom right shows the front view of the helium inlet.

These results in Figure 5 illustrate the thermal distribution in the LBE box, again comparing the performance of the LES model on the right with that of the k-ϵ model on the left. The k-ϵ simulation of the LBE displays a stratified temperature profile, with the majority of the high-temperature regions (ranging from $465\,\mathrm{K}$ to over $1023\,\mathrm{K}$) staying in the core. This implies a low level of internal mixing. In the LES model, the temperature field is more chaotic and spatially varied, exhibiting swirling structures and eddies inside the enclosure. The LES simulation shows improved mixing and heat transport, which helps to identify potential thermal hotspots and improves understanding of flow distribution in the microreactor environment. This demonstrates how LES is useful for capturing complex convective behavior, which is crucial for micro-reactor's safety and thermal control when using HPHE. The results of this study provide theoretical insight into the application of HPHE for heat management in a micro-reactor intended for deployment in power generation.

4 Conclusion

A CFD simulation of the LES and k-ϵ turbulent model on the thermal control of a heat pipe heat exchanger intended for use in micro-reactors was studied. While the two models could be used to facilitate thermal control in an HPHE, the LES model shows a substantial thermal management control than the k-ϵ model. By using the LES, the fine-scale eddies and transitional flow effects in the fluid flow of the HPHE was captured. In contrast to the k-ϵ model, which predicted cooling performance at only $723\,\mathrm{K}$, the LES model resulted in a drop in helium temperature from $1023\,\mathrm{K}$ to $500\,\mathrm{K}$. However, the LES model air outlet temperature was observed to be $722\,\mathrm{K}$ whereas k-ϵ predicted the same air outlet temperature. This study the choice of turbulence models directly affects the thermal efficiency prediction of an HPHE's predicted thermal effectiveness by affecting the fluid outlet temperatures and internal flow behavior visualization. While LES provides higher fidelity but at a higher computational cost, the k-ϵ is still a viable choice for faster evaluations with lower flow feature resolution. To support the results, experimental confirmation of LES predictions is necessary for subsequent research. To strike a balance between accuracy and computational efficiency, future studies should focus on the RANs, k-ω, or hybrid turbulence models like Detached Eddy Simulation.

5 Acknoledgements

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