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Simulation Study on the Heat Performance of Different Nanofluids for Rotating Detonation Engine Cooling

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ABSTRACT

The objective of this numerical study is to analyze the heat transfer performance of different nanofluids for RDE cooling. Based in previous researches, they used water as coolants for their RDE cooling setup but in this research study, instead of using water, nanofluids were used numerically to see whether nanofluids can remove heat better than water, which directly contributes to improvement of RDE cooling system. The nanofluids consists of titanium dioxide, copper oxide and aluminium trioxide nanofluids which were labelled as Nanofluid 1, Nanofluid 2, and Nanofluid 3. The boundary conditions include varying the mass flow rate of 0.0034 kg/s, 0.0102 kg/s and 0.0170 kg/s, with the detonation temperature set to 573K and inlet temperature of 300K and mild steel as the solid part of the model. Based on the simulation result obtained, it shows that Nanofluid 2 possess the best heat transfer performance, which around 26% increase of rate of heat transferred compared to Nanofluid 3 and around 40% increase compared to Nanofluid 1, at mass flow rate of 0.0034 kg/s.

Keywords:
Nanofluids, RDE cooling system, Heat transfer; visible aids

1. Introduction

There are two categories of combustion, which are deflagration and detonation. Internal combustion engines such as piston engines and gas turbine engines use the deflagration type of combustion to produce power. The plausibility of increasing the efficiency through detonation was first proposed by Zel'dovich. In the combustion community currently, the rotating detonation engines (RDEs) are among their specific interest because compared to traditional deflagration engines, RDEs use detonation waves in a rotating manner to combust propellants and increase stagnation temperature and pressure, which results in increase in pressure after combustion while deflagration process also increase temperature with slight loss in stagnation pressure. The alternative aspects of pressure gain combustion vary in how the detonations are manipulated. The two types of detonation engines that gain the interest of the combustion community are pulse detonation engines and rotating detonation engines.

For the RDE, this detonation engine controls an annular injection channel and the propellant flow rate to such a degree that a single detonation wave triggered into the channel travels continuously around the base of the channel. By the time the wave passes continuously, fresh reactants are injected behind it to

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ensure that the moment the detonation wave travels the circumference of the channel, reactants are sufficiently refilled to sustain the wave. Another difference between RDEs and PDEs is the operating frequency. In PDE, the detonations occur in the range between 10 to 100 times per second but for RDE, its wall may be heated by the detonation waves for more than 3000 times per second. As a result, RDEs gain heat at a faster rate and face higher temperature than PDEs. Because of the much heat generated, RDE run times are measured in seconds.

Based on previous studies and experiments, a cooling system was designed for the RDE where it uses water as coolant to remove the heat away. For this numerical study, instead of using water, nanofluids will be used as replacement and will be applied in the simulation that will be conducted to study the nanofluids characteristics and suitability as the cooling element for RDE.

2. Methodology

This study involves multiple systematic methodology, which will be executed in sequence. The first step is to select the three different type of nanofluids for RDE cooling, as well as the suitable mass flow rate of the nanofluids supplied. The next step includes to identify or select the boundary conditions and conducting assurance of the solution method. The third step is initialization of the program and then followed by the final step, which is to execute and simulate the process. It is also very important to validate or evaluate the simulation process with previous researchers to ensure the process are correctly conducted. In general, the research work flow are shown below in Figure 1.

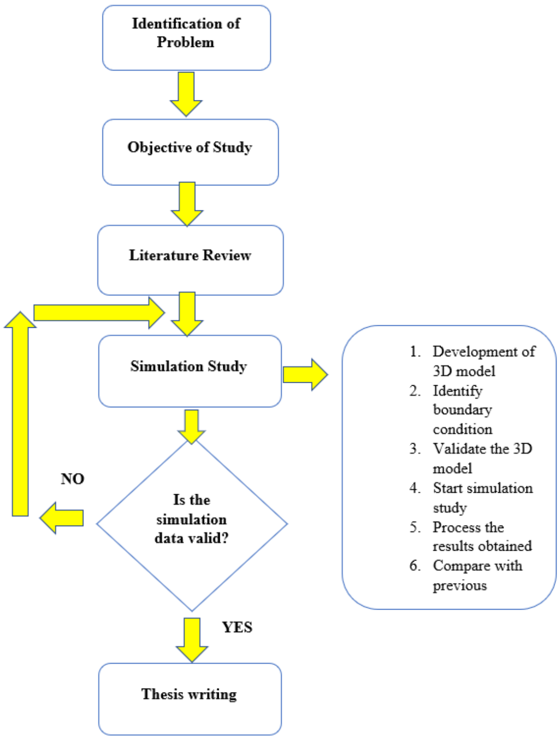

Fig. 1. Process flow of research work

2.1 Simulation Process of ANSYS FLUENT

The 3D cooling model of RDE consist of an inlet, a cooling chamber, where the cooling happens and an outlet. The nanofluids starts flowing through the inlet, then shoots out directly to the wall of

RDE and goes out through the outlet. Below are the dimensions and the 3D model of the cooling system, with the nanofluid flow shown in arrows;

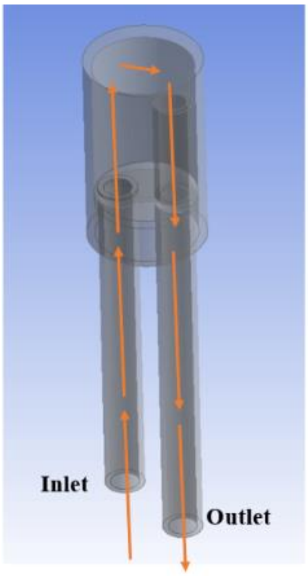

Fig. 2. Three-dimensional model of cooling

Table 2
Dimensions of each part in the model

Model Part	Inlet	Outlet	Cooling chamber
Inner diameter (mm)	10	10	34
Outer diameter (mm)	12	12	36
Length (mm)	125	180	70
Thickness (mm)	2	2	6

For the material of RDE, mild steel was used because it has high melting point, weldable and cost effective. The table below shows the material properties of mild steel;

Table 1
Material properties of mild steel

RDE Material	Mild steel
Density	7700 kg/m^3
Thermal conductivity	46.8 W/m.K
Specific heat capacity	519 J/kg.K

Mild steel is declared as the solid part of the 3D cooling model of RDE in the software. For the nanofluids, there are three which are titanium dioxide, copper oxide and aluminium trioxide nanofluids. The main reasons why nanofluids were choose as the coolant is because of their higher specific surface area which increases the heat transfer between surface and fluids, plus their thermo-physical properties such as thermal conductivity and surface wettability can be adjusted by varying their concentration to suit different applications. The thermo-physical properties of the nanofluids can be seen based on Table 2. Each of the nanofluids were supplied at three different mass flow rate which the rate are at 0.0034 kg/s, 0.0102 kg/s and 0.0170 kg/s.

Table 2
Thermo-physical properties of nanofluids

Label	Nanofluid 1	Nanofluid 2	Nanofluid 3
Type of nanofluid	TiO_2-EG-H_2O	CuO-H_2O	Al_2O_3-H_2O
Thermal conductivity (W/m.K)	0.432	0.616	0.661
Viscosity (kg/m.s)	0.00125	0.000612	0.000612
Density (kg/m^3)	1049.5	1061	1007.4
Specific heat capacity (J/kg.K)	3463.3	3998	4017.8

For the meshing setup, Figure 2 below shows the meshing of the 3D model, which uses maximum face size of 0.1 m. This meshing was achieved after many trials and errors to obtain valid results and prevent any errors from happening.

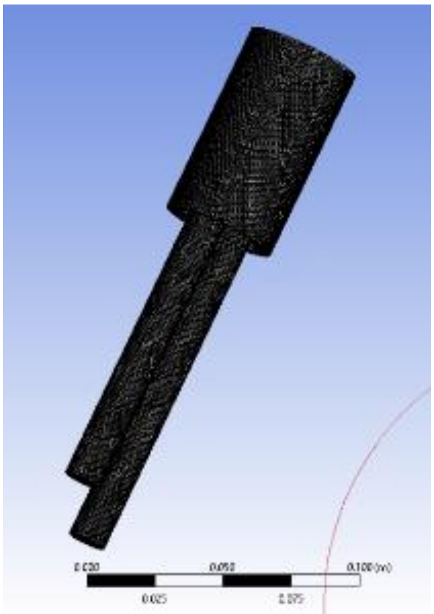

Fig. 2. Meshing of 3D model of cooling

For the boundary conditions, the temperature of detonation was preset to 300°C, and the inlet temperature was set to room temperature which was 27°C. Figure 3 below shows the contour of temperature distribution that have been set.

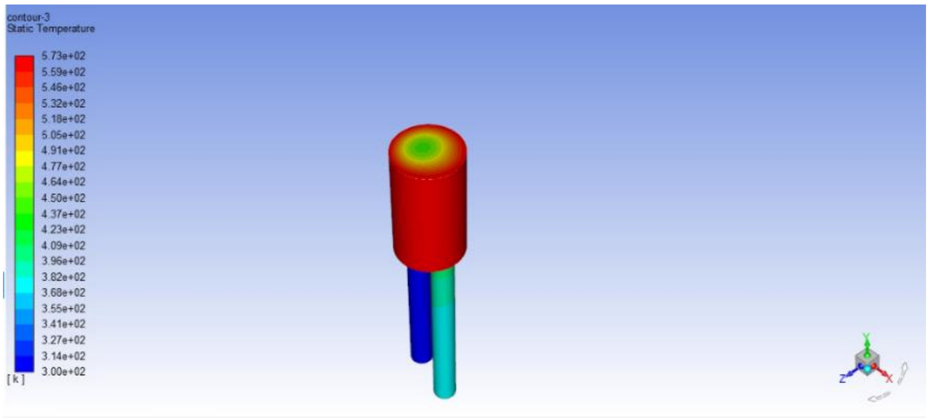

Fig. 3. Temperature distribution of the cooling model

After running the simulation, the next step is to process the data obtained. The data were tabulated and then shown in the form of graph to better understand and analyze the trend produced.

3. Result and discussion

3.1 Heat Transfer Analysis

After running the simulation, the outlet temperature was taken to obtain the value of temperature difference, so that the value of rate of heat transferred can be obtained. Figure 4 below shows the result of temperature difference with increasing mass flow rates.

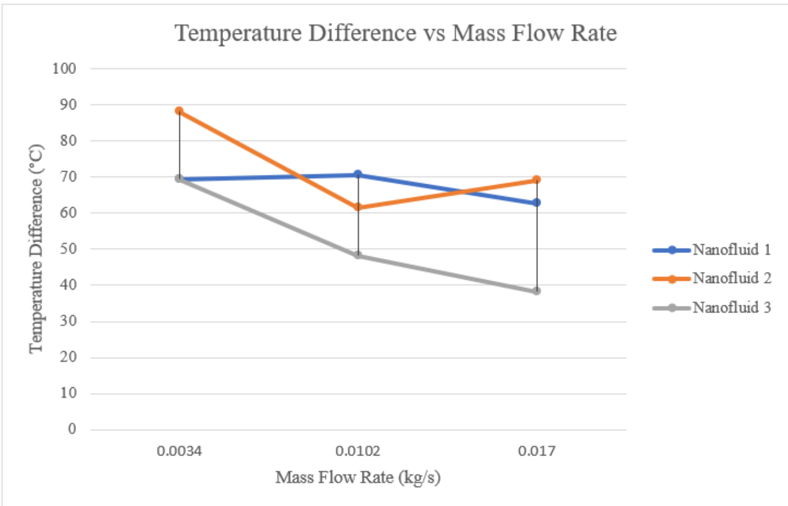

Fig. 4. Graph of temperature difference against mass flow rate

To better explain the outcomes or effect of the mass flow rate of nanofluids towards the heat transfer, based on Figure 5, a graph of heat transfer against mass flow rate of coolant was prepared and it clearly shows that to obtain higher heat transfer, the mass flow rate should be increased. This trend obeys the equation of the heat transfer, $Q = mc\Delta T$, which indicates the heat transfer rate is directly proportional to the mass flow rate. The graph on Figure 5 shows the trendline to further proved the relationship and it also indicates how much heat is being removed from the wall of RDE towards the nanofluids.

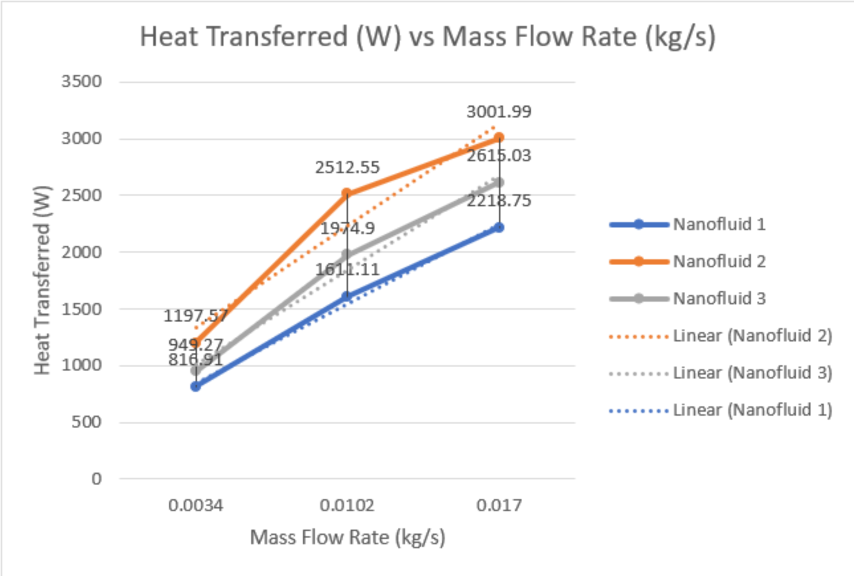

Fig. 5. Graph of heat transferred against mass flow rate

The mass flow rate can be used to determine whether the coolant flow is laminar or turbulent. In practice, the system would be most effective as a cooling system when the flow is turbulent, as no nanofluids are boiled near the wall, as the wall temperature can easily rise to the boiling point of nanofluids in a matter of seconds and could even go much higher if the RDE is set to run for an extended period of time. Figure 6 below shows the graph of Nusselt number against Reynold number.

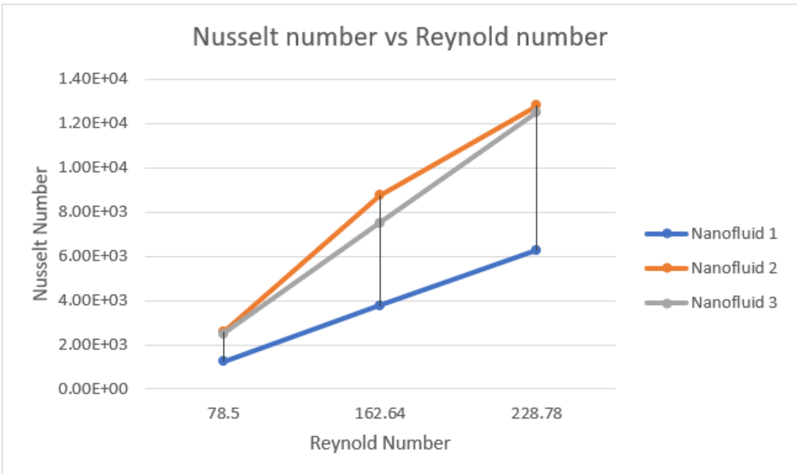

Fig. 6. Graph of Nusselt number against Reynold number

Observed from the standpoint of heat transfer, it is apparent that as the mass flow rate of nanofluids increases, so does the temperature difference between the input and output coolant temperatures, as depicted in Figure 4.3. This demonstrates that increasing the flow rate eliminates the properties of laminar flow, allowing the coolant to flow with a more turbulent nature as a result. When the nanofluid flow is turbulent, it is possible to gain greater efficiency in thermal transfer.

3.2 Validation of Simulation Result

Based on Figure 7, the numerical data obtained through ANSYS FLUENT was valid because both the experimental data and numerical data shows a similar trend of increasing linearly with mass flow rate of nanofluid or water, based on the trendline. At the same time, Figure 4.6 also shows that nanofluid perform better than water as coolants because the heat transferred by nanofluids were much larger compared to water. Even so, the data of the heat transferred for nanofluids was obtained numerically, not experimentally. For better result, it is better to try to run the RDE cooling with nanofluids experimentally.

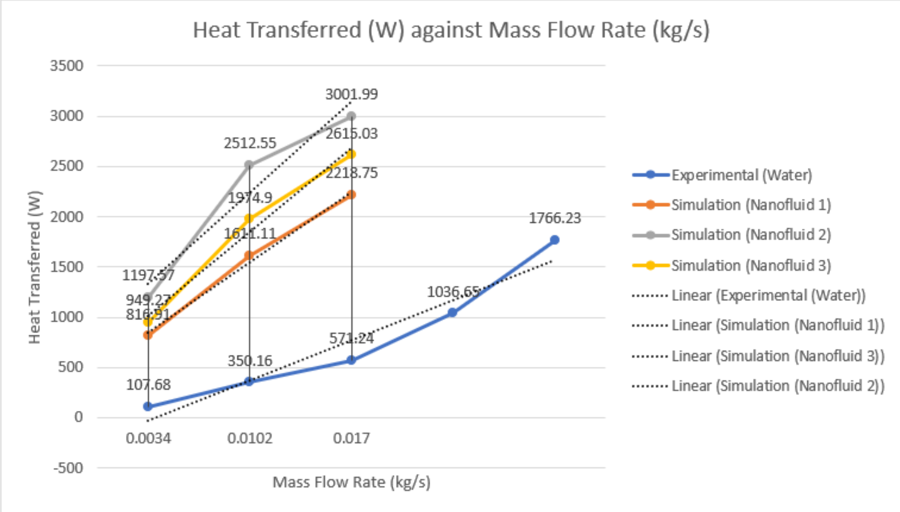

Fig. 6. Comparison between experimental and numerical data

4. Conclusion

In this thesis, the numerical simulation conducted proves that nanofluids can be used to remove heat from the RDE and the result was even better compared to when using water. Three different nanofluids were used, which are titanium dioxide, copper oxide and aluminium trioxide nanofluids, and based on the simulation data and graphs plotted, the best nanofluid that can remove the most heat compared to the other two was the copper oxide nanofluid. This simulation study has achieved the objective, which was to analyze the heat transfer performance of different nanofluids for cooling of RDE. In short, this study has proved that nanofluid can be the best replacement as the coolant for RDE instead of using water. Because this simulation study has successfully met the objectives, this study somehow can be a meaningful beginning to develop and further improvise the RDE cooling system.

Based on the findings obtained from this research, it can be seen that there were issues on the design of the cooling flow of RDE. Thus, it might be good to improve the design of the cooling flow, especially at the inlet, outlet and the way the coolant flows into the core of RDE. The issue that will arise is that there might be some coolants left in the cooling chamber of RDE that may disturb the detonation process. The flow could be design in such a way that the inlet and outlet of the cooling allows the coolant or nanofluid to flow in and out without leaving too much of them in the cooling chamber. Another aspect that need to be improved is the material of the RDE. It is better to use strong and thick stainless steel instead of mild steel because stainless steel tends to have better corrosion resistance, which makes it more durable and long lasting. In short, the suggestions explained perhaps can solve the issues regarding the flow and material of RDE.

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