Jurnal Penelitian Fisika dan Aplikasinya (JPFA)
p-ISSN: 2087-9946
e-ISSN: 2477-1775
Volume 11, Issue 01, June 2021
DOI: 10.26740/jpfa.v11n1.p63-71
https://journal.unesa.ac.id/index.php/jpfa

Research Article

Simulation on the Effect of Coolant Inlet Temperature and Mass-Flowrate Variations to the Temperature Distribution in Single Pellet Thermal Reactor Core

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Abstract

An important factor in the development of nuclear energy is reactor safety. The performance of heat transfer from nuclear fuel to coolant is the main key to the reactor safety. This paper presents simulation on temperature distribution in two-dimensional laminar flow for single pellet thermal reactor with variation on temperature inlet and mass-flowrate. The OpenFoam platform (SimFlow 3.1) has been used for the computational and numerical analysis. The simulation is carried out on a single pellet with an aspect ratio of 1.2. The variations in the mass velocity of the coolant flow are 10, 100, and 14300 kg·s^{-1} with a constant coolant temperature of 552 K, and the variations of the input coolant temperature are 300, 552, and 1000 K with a constant mass-flowrate of 10 kg·s^{-1}. The results obtained from the simulation show that for variations in the input coolant temperature of 300, 552, and 1000 K, the fuel temperature can be reduced respectively by 34, 26, and 14 K. At the fastest variation in the coolant mass-flowrate of 14300 kg·s^{-1}, the coolant temperature around the pellet rises by 396 K. The decrease in fuel temperature is significant if the mass-flowrate of the input coolant flow is relatively low.

Keywords: *Pellet; thermal rector; coolant; flowrate coolant; transient; temperature distribution*

Simulasi Pengaruh Variasi Suhu Masukan dan Laju Aliran MassaPendingin terhadap Distribusi Temperatur pada Pelet Tunggal Reaktor Termal

Abstrak

Faktor penting dalam pengembangan energi nuklir adalah keamanan reaktor. Kinerja perpindahan panas dari bahan bakar nuklir ke pendingin merupakan kunci utama keselamatan reaktor. Simulasi pengaruh variasi suhu masukan dan laju aliran massa pendingin terhadap distribusi temperature untuk pelet tunggal reaktor termal telah dilakukan. Platform OpenFoam (Simflow 3.1) digunakan untuk analisis komputasi dan numerik. Simulasi dilakukan untuk pelet tunggal dengan aspek rasio sebesar 1,2. Variasi laju aliran massa pendingin adalah 10, 100, dan 14300 kg·s^{-1} dengan suhu pendingin sebesar 552 K, dan *variasi suhu pendingin masukan adalah 300, 552, dan 1000 K dengan laju aliran massa pendingin sebesar 10 kg·s*$^{-1}$*. Hasil yang diperoleh dari simulasi menunjukkan bahwa untuk variasi suhu input pendingin 300, 552, dan 1000 K, suhu bahan bakar berkurang masing-masing sebesar 34, 26, dan 14 K. Pada laju aliran massa pendingin sebesar 14400 kg·s*$^{-1}$ *maka suhu pendingin di sekitar pelet naik sebesar 396 K. Penurunan suhu bahan bakar cukup signifikan jika laju alir massa aliran pendingin masukan relatif lambat.*

Kata Kunci: *pellet, reaktor termal; pendingin; laju alir massa; transien; distribusi temperatur*

PACS: 07.20.Dt; 47.11.-j; 47.85.-g; 47.85.Np

Article History: Received: August 22, 2020 Aproved with minor revision: May 4, 2021
Accepted: July 18, 2021 Published: June 30, 2021

Howtocite: Yusibanil E, et al. Simulation on the Effect of Coolant Inlet Temperature and Mass-Flowrate Variations to the Temperature Distribution in Single Pellet Thermal Reactor Core. *Jurnal Penelitian Fisika dan Aplikasinya (JPFA)*. 2021; **11**(1): 63-71. DOI: https://doi.org/10.26740/jpfa.v11n1.p63-71.

I. INTRODUCTION

An important factor in the development of nuclear energy is reactor safety. The performance of heat transfer from nuclear fuel to coolant is the main key to the reactor safety. Poor heat retrieval performance will threaten the resistance of the fuel assembly which in turn will generate an uncontrolled release of radioactive substances into the environment thereby endangering the safety of reactor workers, the community, and the environment. The issue that is always posed in using nuclear reactors is the accumulation of radioactive substances in the fission product yielded in the core of the reactor. Given this issue, the reactor is required to operate at the right power level with a cooling system that can transfer the heat from the reactor core maximally. The application of very strict safety requirements needs to be done for the construction of nuclear reactors and their operation [1]. Talking about safety factors, the role of thermal hydraulic parameters becomes very important because they can limit reactor operation. The thermal hydraulic parameters are, for examples, core pressure drop, coolant temperature distribution, fuel cladding temperature and fuel temperature. Flow and temperature distributions in a high flux reactor using the porous media approach with FLUENT have been predicted by Huang S, et al. [2], and they found that the inlet coolant mass flow rate require greater than 450 kg/s to ensure the key requirements for safety [2]. Heat transfer phenomenon with a different initial water heater temperature by using NC-Queen apparatus constructed with rectangular loop have been investigated by Juarsa M, et al. [3].

Convection is a method for heat transfer. Convection itself consists of forced and natural convection. Forced convection is a heat transfer performed manually, such as the force from the pump, while natural convection occurs due to the difference in density of the fluids. This difference causes the low-density fluid will move up (in hotter regions) and the higher density fluid will move down (in the cooler section). Natural convection phenomenon can be observed in the process of heating water and sea water currents. The application of natural convection phenomena is used in cooling systems in nuclear reactors. In the conventional case, cooling water in the reactor is driven by pumps. Nowadays, a lot of discussion is starting to use natural convection phenomena to drain fluid so that the coolant fluid can still flow when the pump is not available. Research on natural convection on the reactor core has been widely carried out by researchers [4-8]. From the research, it could be concluded that natural convection requires in a closed loop system depending only to the temperature differences with a certain geometry of the fuel.

A simulation on the dynamical response of a counter current heat exchanger to inlet temperature or mass flow rate change has been done. The behavior of the system may affect by the change of parameters of inlet temperature or mass flow rate. A change in any of these parameters lead to an unsteady behavior in the whole system [9]. A multi-scale coupling method was proposed with CFD (computational fluid dynamics) and sub-channel analysis to investigate the lateral flow upper plenum reactor and temperature heterogeneity in the hot legs of AP1000 reactor. It is founded that the maximum temperature difference at the entrance of the hot leg drops is 10.0 K [10]. Effect of axial porosity distribution of the packing material on the heat transfer distribution was analyzed. The use of a variation of the porosity with packed bed depth showed especially a better representation of the deeper thermocouples data. the advanced porosity models allow reducing the pressure drop simulation error from 40 % down to 11 % obtained with the constant porosity model [11]. A simulation of Loss-of-Flow transient by the means of CFD has been done in the MYRRHA reactor. Once the core is scrammed, the levels of the lower and upper plenum equilibrate roughly 20 s after the pump failure event [12]. The flow characteristics in the pressurized water reactor with different internal structures is done by CFD simulation. The mass flow rates in center fuel assemblies are higher than that in peripheral fuel assemblies at core inlets [13]. Many researchers have made detailed analysis on the coolant mixing in the reactor, flow field in the reactor pressure vessel, flow distribution at core inlets using CFD methods [14-22], however the behavior of single pellet in a reactor nuclear, PWR type, due to variation on inlet temperature and mass flow rate has not been investigated as a fundamental study.

The purpose of the present study is simulating temperature distribution in a single pellet of thermal reactor core with variations in inlet temperature and mass flow rate of the coolant.

II. METHOD

The thermal and flow fields are simulated using SimFlow 3.1. This software is commonly used in science and engineering to estimate the efficiency of devices [23,24]. SimFlow is a powerful general-purpose CFD software. It combines an intuitive graphical user interface with the advantages of the open-source OpenFOAM® libraries.The data used in the present study are obtained from the AP1000 pressurized water reactor. This data is needed to determine the geometry size of the simulation. The computational mesh for the reactor fuel pellet is made using the geometry tools available in the software. The simulation is carried out on a single pellet with an aspect ratio of 1.2 (height: 0.098 m, radius: 0.04095 m) (Figure 1). The variations in the mass flowrate of the coolant flow are 10, 100 and 14300 $kg \cdot s^{-1}$ with a constant coolant temperature of 552 K, and the variations of the input coolant temperature are 300, 552, and 1000 K with a constant mass-flowrate of 10 $kg \cdot s^{-1}$. The reactor core is designed in two dimensions in the form of a square with sides of length 1m and the origin of the x-y coordinate system at the center. The fuel pellet material used in the present simulation is covered with iron and the fluid coolant is water under apressure of 15 MPa. The initial temperature condition in the pellet and coolant are 1500 K and 300 K, respectively. The program is run by setting the start time at 0 s and the finish time at 80 s with a sweeping time of 1 s. The scenario in the present simulation is transient fluid and heat transfer between pellets and cooling material. For such cases, the *chtMultiRegionFoam* solver is chosen where the fluid flow is considered in two phases, i.e. the solid and the liquid phase.

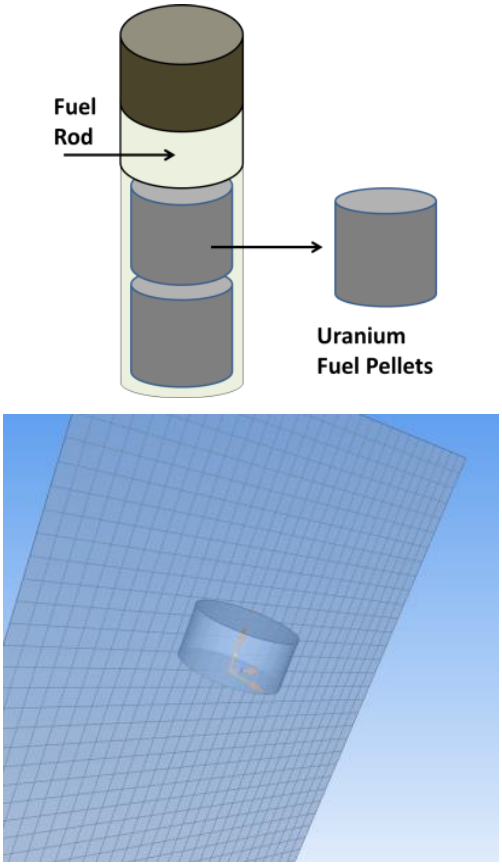

Figure 1. Typical Arrangement of Fuel Pellet in Fuel Rod for Thermal Reactor Nuclear Core and Meshing Geometry

III. RESULTS AND DISCUSSION

Variation on mass-flow rate at constant inlet temperature

The simulation results for the variation of mass-flow rate are shown in Figure 2. Coolant input and fuel temperature are constant at 552 and 1500 K, respectively, for a mass-flow rate of 10 kg·s^{-1}, temperature changes occur at 0 s to 10 s. After passing through the fuel with a temperature of 1500 K, the coolant temperature, which initially had a value of 552 K, has increased to around 800 K in the x-, x+ and y- axis, while on the y+ side, which is the outlet side, the temperature rises to around 1200 K. The temperature change continues to increase up to 60 s, and from 60 s to 80 s it becomes constant. At a flow rate of 100 kg·s^{-1}, the temperature change occurs at the 10 seconds around 950 K on the x-, x+ and y- sides of the pellet, while at y+ which is the outlet side, the temperature changes to around 1300 K. From 10 to 80 s, there is no significant change in the temperature.

Investigating of mass flow rate Effect on the heat transfer phenomena in a tube and shell heat exchanger have been done by Ruiz LD, et al. [25] and Murugesan MP and Balasubramanian R. [26], typically when the increase in mass flow within the limits defined in the case study while maintaining the temperatures makes this parameter increase proportionally for both global heat transfer coefficients. Based on the present simulation results related to the effect of mass-flow rate on the temperature distribution in the core, it can be found that the faster mass-flow rate, as much as 14300 kg·s^{-1}, causes the cooling ability to decrease. This was shown in the mass flow rate of 14300 kg·s^{-1} of coolant around the pellets which increased in temperature to 1200 K since the first second and subsequent temperatures became constant. The results of this simulation are in accordance with the results of a previous study conducted by Adi AR and Arsana IM. [27] and Wang Y, et al. [28] that the higher the rate of mass flow, the lower the heat transfer. The mass flow rate will affect the temperature distribution in the reactor [29].

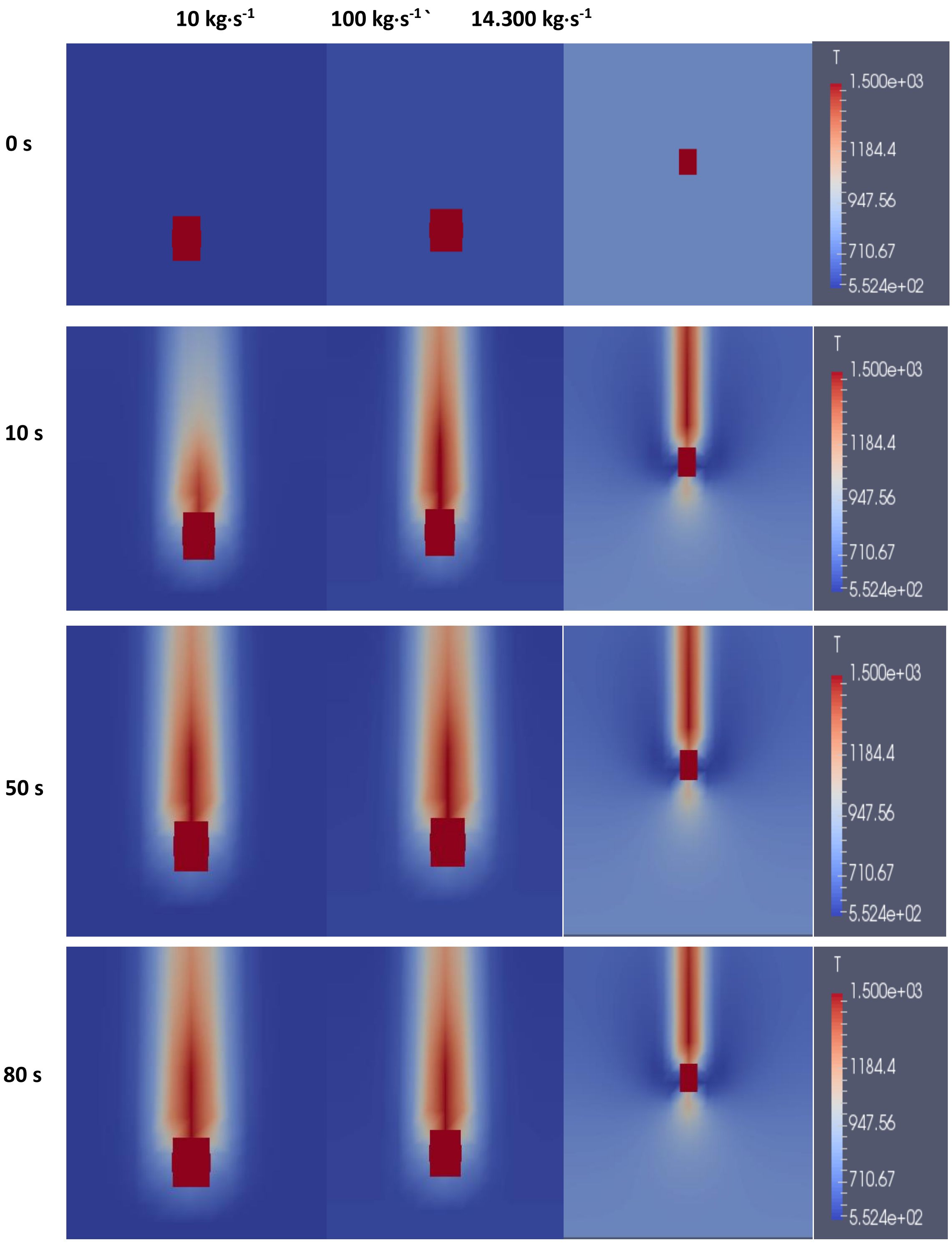

Figure 2. Temperature Distribution of Single Pellets with Coolant Mass-Flow Rates of 10, 100, and 14.300 kg/s

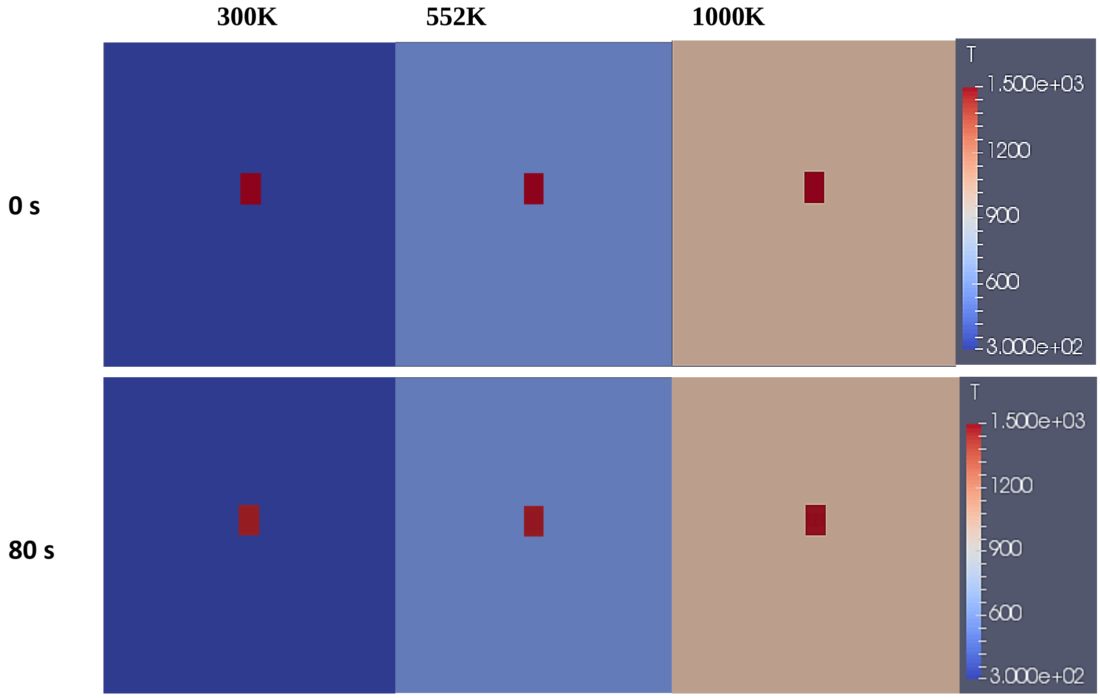

Figure 3. Temperature Distribution of Single Pellets with Temperature Inlet of 30, 552, and 1000 K with Constant Coolant Mass-Flow Rates of 10 kg/s

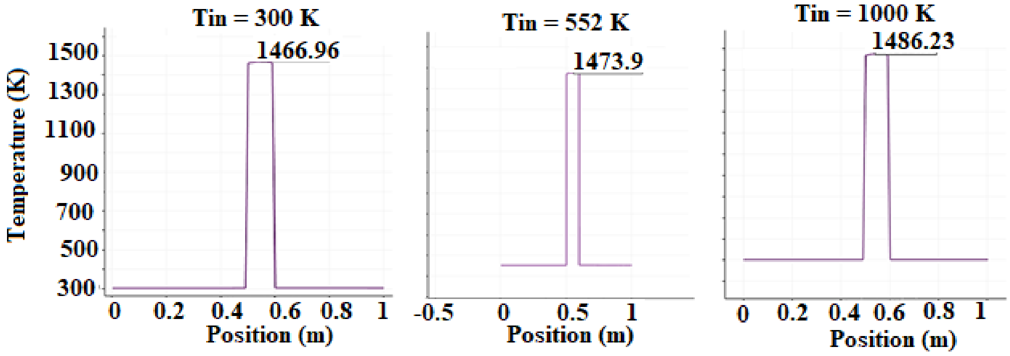

Figure 4. Temperature Distribution of Single Fuel Pellet Versus Position in 80 Seconds

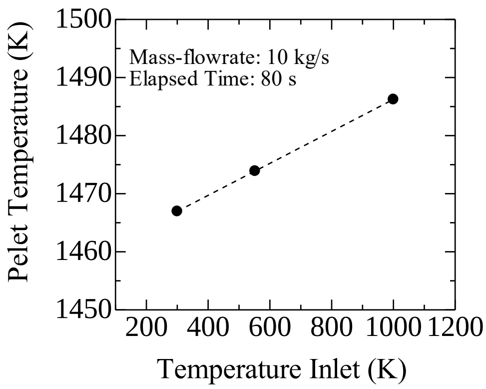

Figure 5. Temperature Decreased at Single Pellet Varied with Inlet Coolant Temperature

Variation on inlet temperature at constant mass-flowrate

According to AP100 [30], the input temperature for PWR AP1000 is 552K. In this simulation, the input coolant temperature varies from 300, 552, and 1000 K. The constant input parameters are mass-flow rate of 10 kg·s^{-1}, the pressure core of 15 MPa and the calculation time up to 80 s. The mass-flow rate is set at 10 kg·s^{-1} to highlight the influence of the input temperature. The results of temperature distribution simulation are shown in Figure 3. The figure shows that the fuel temperature, after a coolant with a temperature of 300, 552, and 1000 K goes through the fuel at a speed of 10 kg·s^{-1}, drops to 1467, 1473, and 1486 K, respectively, in 80 s, as can be found in Figure 4. The coolant causes a decrease in fuel temperature by 34, 26, and 14 K, respectively (Figure 5). The results of this simulation are in accordance with the results of a previous study conducted by Murugesan MP and Balasubramanian R. [26] that the incoming temperature of the fluid will affect the thermal capacity of the system. The difference of 10 degrees will change the heat transfer coefficient (h) by about 0.052 W/m^{2}K. The results show that the higher the input temperature is given, the smaller the fuel temperature decreases.

IV. CONCLUSION

Based on the results of simulations and discussions that have been obtained in the present study, it can be concluded that the speed of the input coolant mass-flowrate and the inlet temperature gradient influence the temperature distribution in the reactor core. The effect of mass-flowrate on the temperature distribution in the core, it can be found that the mass-flowrate beyond the optimum value causes the cooling ability decreases. The decrease in fuel pellet temperature is better if the input coolant temperature is relatively low.

ACKNOWLEDGMENT

The authors would like to acknowledgement Dr. Peter Woodfield for valuable discussion. This research is funded by Faculty of Mathematics and Natural Science under internship program with Dean SK NUMBER of 2039/UN11/KPT/2019 and PKKM-PSF 2021.

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