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Dynamic Thermal Control of Nanofluid Systems: A Numerical Approach to Evaluate Performance of Proportional, Proportional-Integral, and Proportional-Integral-Differential Controllers in Hybrid Cooling Circuits

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Abstract

Purpose – This study numerically investigates the combined effects of a constant cooling circuit and a variable cooling circuit inside a square enclosure having vents with Al₂O₃-water nanofluid using P, PI, and PID controllers.

Design/methodology/approach – The cavity contains two constant inlet ports, two controlled inlet ports, an outlet port, four isothermal cylindrical heat sources, and a temperature probe at the center of the cavity to evaluate the temperature and return feedback to the flow controllers continuously. The surrounding walls are at ambient temperature, and the nanofluid discharge is at ambient conditions at the outlet. The controllers control the inlet flow velocity and the oscillations, overshoot, settling time and steady state error in the values of the temperature (θ) taken nondimensionally at the center are analyzed. The governing Navier-Stokes and energy equations are solved through the Galerkin finite element method with appropriate initial and boundary conditions. Simulations were carried out for proportional gain ($K_p = 0.001, 0.002, 0.003 \text{ ms}^{-1}\text{K}^{-1}$), the integral gain ($K_i = 0.011, 0.013, 0.015 \text{ ms}^{-2}\text{K}^{-1}$), and the derivative gain ($K_d = 0.0001, 0.0003, 0.0005 \text{ mK}^{-1}$) for three different controllers. Calibration of different controllers (P, PI, and PID) is done in a systematic manner.

Findings – The results illustrate that the PID controller yields the best thermal management. Using only the P controller, there always remains a steady state error, which is eliminated by the PI controller. The PI and PID controllers, on the basis of settling time and overshoot, have similar levels of performance.

Originality/value – The evaluation of P, PI, and PID Controllers in Hybrid Cooling Circuits gives useful insights into optimal use of nanofluids and controllers for cooling and the techniques to optimize the controller parameters for enhanced thermal stability and performance commonly seen in microelectronics or bio-electronics.

Keywords: Nanofluid Heat Exchanger; PID controller; Variable Cooling Circuit; Constant Cooling Circuit; Electronic cooling.

1. Introduction

The devices that allow optimum heat transfer and exchange of thermal energy between two flowing fluids at two different temperatures are called heat exchangers. These have been used in almost all thermal engineering fields. Some of the key sectors of the use of heat exchangers are manufacturing industries, electronics, refrigeration, air-conditioning, and space applications. These applications have been highlighted by Pordajani et al [1]. Moreover, cross-flow micro heat exchangers are gaining popularity for heat transfer in compact industrial settings like aerospace, fuel processing, biomedical, and microelectronics. These sectors demand small, efficient coolers with high heat flux potential. Recent advancements in nanotechnology and specialized fluids hold promise for elevating the flow and thermal properties of heat exchangers. Nanotechnology breakthroughs have led to the inception of nanofluids, a distinct class of fluids composed of liquid suspensions containing particles less than 100 nm. These particles boast enhanced thermal conductivity compared to the base liquids. Nanofluids have demonstrated efficacy as working fluids in systems employed for heat transfer, like heat exchangers and heat pipes, due to their nano-sized solid particles, which augment the overall thermal conductivity beyond that of the carrier fluid alone. PID control utilizes three main modes: proportional, integral, and derivative. The term, proportional, adjusts the controlled output on the basis of error (the difference considered within the process variable and the setpoint). The integral term reduces the offset over time by examining the integral of the error. The derivative term evaluates the changing rate of the process variable and adjusts the output accordingly to handle sudden variations. Users can adjust each parameter to achieve the desired performance. PID controllers are widely used due to their simplicity, ease of implementation, and maintenance across various industries such as motion control, power electronics, process control, pneumatics, manufacturing, and hydraulics. They offer a good performance-to-cost ratio compared to other controllers. Moreover, these are increasingly utilized for modern applications like unmanned aircraft vehicles, self-driven cars, unmanned aircraft vehicles, and automated robots. In most control system applications, about 90-95% of controlled loops utilize PID controllers.

Over the years, numerous research works have been conducted to evaluate the thermal transport properties of nanofluids. Initially, Xuan & Li [2] investigated the procedures to prepare nanofluids, which consisted of a suspension of nanophase powder in a base liquid. They observed the thermal

properties of the fluid and established the impacts of volume fraction, physical parameters, and properties. Furthermore, Eastman et al. [3], in their research work, stated that nanofluids comprising nanoparticles of copper in ethylene glycol suspension exhibited significantly higher thermal conductivity compared to the pure form of ethylene glycol with a similar volume fraction of oxide-dispersed nanoparticles. Specifically, incorporating around 0.3 volume % nanoparticles of copper with an average diameter results in an increase of 40% in the effective ethylene glycol thermal conductivity. Moreover, Li and Kleinstreuer [4] evaluated the thermal transport of nanofluid flow in microchannels by developing two effective thermal conductivity models, which came to the conclusion that thermal performance in nanofluids increases with volume fraction for CuO-water ranging from 1% to 4% but comes with and added pressure drop, but have nominated nanofluids to be good candidates for cooling microchannel heat sinks. Amongst the most recent works, Dorin Lelea [5] studied the thermal and fluid transport of Al_2O_3 -water nanofluid through microchannels, and the research focused on local heat transfer coefficients derived from consistent pumping power. The findings uncovered distinct local heat transfer characteristics compared to those analyzed under constant Reynolds number conditions and various volume fractions. Kumar et al. [6] performed an experimental investigation on the conductivity, thermal transfer, and friction factor of Al_2O_3 based nanofluid, under the conditions of fully developed laminar and turbulent flow for shell and tube heat exchangers for different liquids and volume fractions. The base fluids considered were water, paraffin, and ethylene glycol. The outcome of the study was that heat transfer varied significantly with base fluids, volume fractions, and turbulence. Gkountas et al. [7] in recent times have studied the impact of the interfacial layer nanoparticles on heat transfer of a printed – circuit heat exchanger with Al_2O_3 -water nanofluid. With a maximum nanoparticle volume fraction of 5%, it effectively solves the critical cooling process. This results in a remarkable 75% improvement in the thermal transfer coefficient, resulting in 1% reduction in heat exchanger length. However, there is an associated 8% increase in pressure drop. Increasing the radius of nanoparticles leads to a decrease in effective heat conductivity. However, the thickness of a 2 nm nanolayer demonstrated a 43% improvement in thermal transport coefficient in comparison to the 0.5 nm minimum thickness. It was concluded that particles with similar radius and thickness within the nanolayer can result in the enhancement of the heat exchanger performance.

Heat transfers in enclosed spaces occur primarily due to convection, which also affects the fluid flow. Oh et al. [8] evaluated natural convection and thermal transfer in a cavity with a heat-generating conducting body and calculated the performance parameter, Nusselt number, and found the relation of heat transfer characteristics with temperature difference and Rayleigh numbers. Fu and Tong [9]

performed numerical simulations to study the flow structures and heat transfer characteristics of a heated transversely oscillating cylinder in a cross flow, adopting the Lagrangian–Eulerian kinematic description method to describe the flow and thermal fields. The impacts resulting from the oscillating speed, Reynolds number, oscillating amplitude, and impact on the heat transfer and flow structures have been examined in their investigation. From their study, they could conclude that heat transfer and flow properties come to a periodic state after a certain time. Moreover, Wang et al. [10] conducted experiments on heat transfer enhancement for shell and tube heat exchangers. Their studies revealed notable improvements in the shell-side heat transfer coefficient, increasing by 18.2–25.5%, and overall heat transfer coefficient, rising by 15.6–19.7%, for the enhanced heat exchanger. Additionally, exergy efficiency saw an increase of 12.9–14.1%. Despite a rise in pressure losses by 44.6–48.8% due to sealer installation, the associated increment in required pump power was negligible when compared to the rise in heat flux. Numerical investigation was conducted by Soares et al. [11], which explored how drag components and heat transfer characteristics vary in the incompressible and steady regimes of flow of fluids characterized by the power-law non-Newtonian properties over an unconfined, heated circular cylinder. It assessed the impact of Prandtl number ($1 \leq Pr \leq 100$), power-law index ($0.5 \leq n \leq 1.4$), and Reynolds number ($5 \leq Re \leq 40$). Moreover, Farajollahi et al. [12] in their research work on the heat transfer in shell and tube heat exchangers with nanofluids, where the comparison of heat transfer behavior between two nanofluids showed that, at a specific Peclet number, TiO₂/water nanofluid exhibits superior heat transfer characteristics at its optimal nanoparticle concentration compared to γ -Al₂O₃/water nanofluid. However, γ -Al₂O₃/water nanofluid demonstrated better heat transfer behavior at higher nanoparticle concentrations. In recent times, Ahmed et al. [13] evaluated laminar convective heat transfer of Al₂O₃ -water nanofluid flow over tube banks under constant wall temperature conditions for different Reynolds numbers, volume fractions, and physical geometry and found the best thermal performance for these parameters.

PID feedback control is the most used control method to control temperature, humidity, speed, and other process variables. To control air curtains for fire-induced smoke confinement in a tunnel configuration, Yu et al. [14] observed that air curtains can effectively meet the requirements of smoke control in different complex fire scenarios by PID-controlled tuning approaches. A PID controller is used to control discharging performance in a latent heat energy storage unit by Zhang et al. [15]. Shuvo et al. [16] used P, PI, and PID for internal cooling of an enclosed cavity by controlling inlet flow velocity. Elhosseini et al. [17] investigate the shrink and swell phenomenon inside HRSG power plants and use FOPID and a fuzzy controller that improved system responses compared to the conventional optimal controller. The stiffness of the magnetic bearing decreases significantly due to the eddy current effect.

Sun et al. [18] included a dynamic stiffness model for the PID parameter tuning method for the radial active magnetic bearing (RAMB) control system, and Satisfactory control effects consistent with the theoretical analysis were obtained. Saha et al. [19] used P, PI, and PID controllers to modulate the T-shaped inlet flow in a cavity kept open to maintain constant temperature at a specified location and found that the PID controller performs better than the P and PI controllers.

From the above literature review survey, it is evident that no studies were conducted to control the two inlets flow of a water- Al_2O_3 nanofluid cooled square vented cavity containing four discretely heated cylinders using different controllers, such as P, PI, and PID. Proper monitoring and maintenance of optimal temperature, humidity, speed, and all the different process variables can be done through continuous controllers with precision and are already widely being used in the industry. Nowadays, researchers are aiming for the development of PID control systems in industry. This present study observes and controls the temperature inside the cavity by convective flow, applying these controllers. The performance of P, PI, and PID controllers was observed, and results were presented.

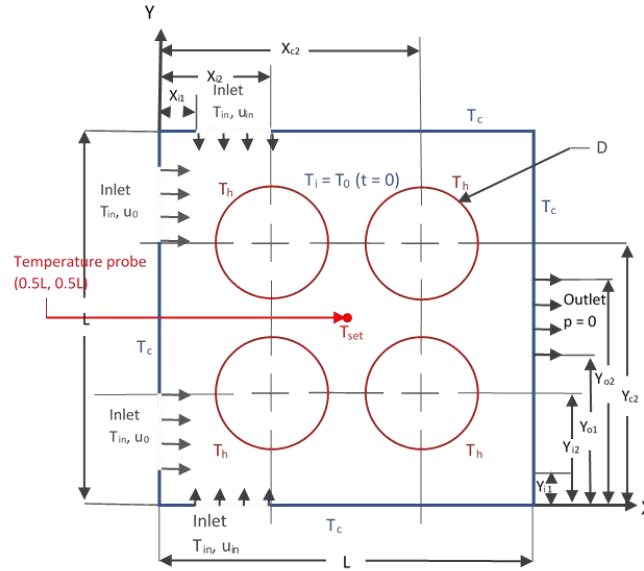


Fig. 1. Schematic diagram of the vented square enclosure with four isothermal circular heat sources.

2. Physical Modeling

The studied domain with proper boundary conditions and initial conditions is illustrated in Fig. 1. The square cavity has a length, $L = 0.01$ m. There are four circular isothermal heat sources in the

enclosure. The surface temperature of the heat sources is maintained at $T_h = 353$ K. The isothermal heat sources have a diameter of $D = 0.3L$. The center of all the heat sources is located $0.3L$ away from the walls.

The insulated walls are maintained at $T_c = 290$ K. The domain has an initial temperature of $T_i = T_0 = 290$ K. A nanofluid (Aluminum Oxide, Al_2O_3 in water with $\phi = 0.02$ volume fraction) is employed for cooling the cavity. There are four inlets and one outlet for fluid flow across the domain. All the inlets and outlets have a length of $0.2 L$. Two of the inlets (located at $y = 0.1L$ and $y = 0.7L$ height of the left wall) are kept at a constant velocity of $u_0 = 0.0075$ m/s. A temperature probe is set at the midpoint ($0.5L, 0.5L$) of the enclosure to measure the temperature T_p instantaneously. A set temperature of $T_{set} = 300$ K must be maintained at the probe point by regulating the other two inlet velocities, u_{in} (on the upper and lower wall at $x = 0.1L$). The flow is controlled by using a P, PI, or PID controller with optimized values of K_p , K_i , and K_d .

The Maiga model is used for the dynamic viscosity of nanofluid from Pak and Cho (1998) [20]. The property for water is taken at 300 K from Cengel and Ghajar(2015) [21]. The model for nanofluid density was like the one used in Fares et al. (2016) [22]. According to Selimefendigil et al. (2021) [23], the Maxwell Garnet model is used for the thermal conductivity of nanofluid.

Table 1: Property Table

Property Name	Value/Range	Description
ρ_f	997.1 (kg/m ³)	Water density
ρ_s	3970 (kg/m ³)	Aluminium oxide's density
$(c_p)_f$	4179 J/(mol K)	Heat capacity of base fluid at constant pressure
$(c_p)_s$	765 J/(mol K)	Heat capacity of aluminium oxide
κ_f	0.613 (W/(m K))	Thermal conductivity of the base fluid
κ_s	40 (W/(m K))	Thermal conductivity of alumina
ϕ	.02	Volume fraction
ρ_{nf}	$(1 - \phi)\rho_f + \phi\rho_s$	Density of nanofluid
μ_f	0.00081 [Pa * s]	Viscosity of water
μ_{nf}	$(1 + 7.3\phi + 123\phi^2)$	Dynamic viscosity of nanofluid
G	9.8 m/s ²	Acceleration due gravity
κ_{nf}	$\kappa_f \frac{\kappa_s + 2\kappa_f - 2\phi(\kappa_f - \kappa_s)}{\kappa_s + 2\kappa_f + \phi(\kappa_f - \kappa_s)}$	Thermal conductivity of nanofluid Maxwell Garnet model
$(\rho c_p)_f$	$\rho_f \cdot (c_p)_f$	Heat capacitance of fluid
$(\rho c_p)_s$	$\rho_s \cdot (c_p)_s$	Heat capacitance of solid
$(\rho c_p)_{nf}$	$(1 - \phi)(\rho c_p)_f + \phi(\rho c_p)_s$	Heat capacitance of nanofluid
α_{nf}	$\frac{\kappa_{nf}}{(\rho c_p)_{nf}}$	Thermal diffusivity of nanofluid

3. Mathematical Modeling

In modeling the mathematical model of the system, continuity, momentum, and energy equations are used. The equations are to be solved with the initial and boundary conditions to predict the thermal and flow field variables. The fluid to be used is alumina nanofluid, which is incompressible. The equations(1-4) are as follows :

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \quad (1)$$

$$\rho_{nf} \frac{\partial u}{\partial t} + \rho_{nf} \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial p}{\partial x} + \mu_{nf} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

$$\rho_{nf} \frac{\partial u}{\partial t} + \rho_{nf} \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial p}{\partial x} + \mu_{nf} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (3)$$

$$\rho_{nf} C_{p,nf} \frac{\partial T}{\partial t} + \rho_{nf} C_{p,nf} \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = K_{nf} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

The Cartesian coordinates (x, y) are considered, alongside, t is taken to be the coordinate of time and the velocity components, u and v of the nanofluid, T is nanofluid temperature, P is the pressure of the nanofluid, k_{nf} is the considered to be the thermal conductivity of Al_2O_3 , $C_{p,nf}$ is the specific heat of Al_2O_3 nanofluid, μ_{nf} is the dynamic viscosity of Al_2O_3 nanofluid, ρ_{nf} is the density of Al_2O_3 nanofluid, and g is the gravitational acceleration. The decided conditions along the boundary walls applied in this study are presented in Table 2.

Table 2: Appropriate auxiliary conditions are considered for the current study.

Boundary	Thermal State	Hydrodynamic State
Heat sources	$T_h = 353 \text{ K}$	$u = v = 0 \text{ ms}^{-1}$
Controlled inlets	$T_{in} = 293 \text{ K}$	$v = 0 \text{ ms}^{-1}$; $u = u_{in}(t, T_p, K_p, K_i, K_d) \text{ ms}^{-1}$ if $T_p \geq T_{set}$ and $u = 0 \text{ ms}^{-1}$ if $T_p < T_{set}$
Constant inlets	$T_{in} = 293 \text{ K}$	$v = 0 \text{ ms}^{-1}$; $u = u_0 = 0.0075 \text{ ms}^{-1}$
Outlet	$\partial T / \partial x = 0 \text{ Km}^{-1}$	$v = 0 \text{ ms}^{-1}$; $\partial u / \partial x = 0 \text{ s}^{-1}$ and $p = 0 \text{ Pa}$
Walls	$T_c = 293 \text{ K}$	$u = v = 0 \text{ ms}^{-1}$

The selection of the continuous controllers impacts the inlet velocity significantly, which is expressed in equations (5-7) as follows:

P controller:

$$u_{in} = K_p(T_p - T_{set}) \quad (5)$$

PI controller:

$$u_{in} = K_p(T_p - T_{set}) + K_i \int (T_p - T_{set}) dt \quad (6)$$

PID controller:

$$u_{in} = K_p(T_p - T_{set}) + K_i \int (T_p - T_{set}) dt + K_d \frac{d(T_p - T_{set})}{dt} \quad (7)$$

In the model, T_p is the temperature sensed by the probe at the designated point. A probe point is taken where the temporal temperature response, taken non-dimensionally, is measured, and the performance

across different parameters, as well as different controller combinations, is also benchmarked. Thus, this yields the temperature which is converted into a non-dimensional parameter as follows:

$$\theta = \frac{T_p - T_0}{T_{set} - T_0} \quad (8)$$

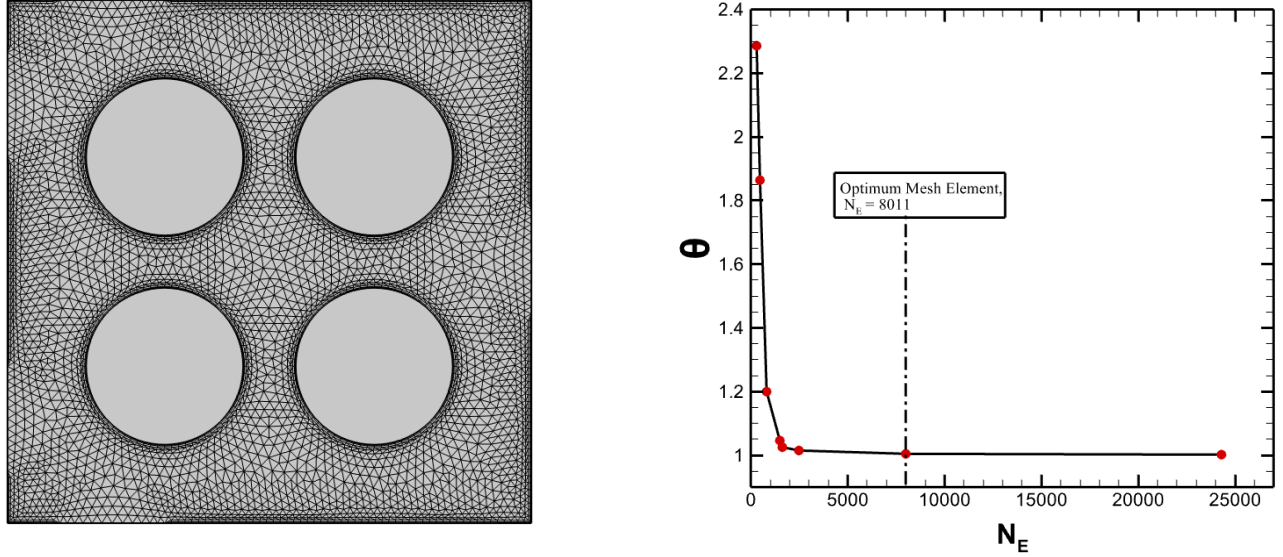


Fig. 2: (a) Computational Mesh deployed in the nanofluid domain (b) Grid Independence Test for the model test run in terms of Θ at $t = 2.25s$ and for $K_p = 0.0003 \text{ ms}^{-1}\text{K}^{-1}$, $K_i = 0.012 \text{ ms}^{-2}\text{K}^{-1}$, and $K_d = 0.0001 \text{ mK}^{-1}$

4. Numerical Procedure, Grid Independence Test and Model Validation

The Galerkin finite element technique is utilized to solve the dimensional governing equations specified in the equations of the nanofluid domain for the specified boundary conditions (refer to Table 2). The computational domain is discretized into multiple finite elements (shown in Fig.2(a)), determined through a mesh sensitivity test (shown in Fig.2(b)). Function approximation involves employing piecewise trial functions over each of these elements. Linear interpolation functions are used to approximate flow variables, and simplification is achieved through Newton-Raphson iteration methods.

Parametric investigations of the current problem involve varying the P, PI, and PID parameters, K_p , K_i , and K_d of the nanofluid domain. It's noteworthy that the parametric simulation of the computational model is carried out using the commercial software COMSOL Multiphysics 6.2.

A grid independence test is crucial for validating the precision and reliability of numerical simulations. It involves adjusting the mesh or grid resolution in a computational model to evaluate how sensitive the results are to changes in grid size. The objective is to guarantee that the simulation outcomes remain largely unaffected by the grid and converge reliably to a stable solution with grid refinement. In this simulation, the grid size is varied from extremely coarse to extra fine, with the number of elements (Ne) varying from 100 to 24000. The variation in the result becomes negligible at a higher number of mesh elements. In order to maintain the optimal balance between computational cost and solution accuracy, the optimum mesh with a number of elements of 8011 has been selected.

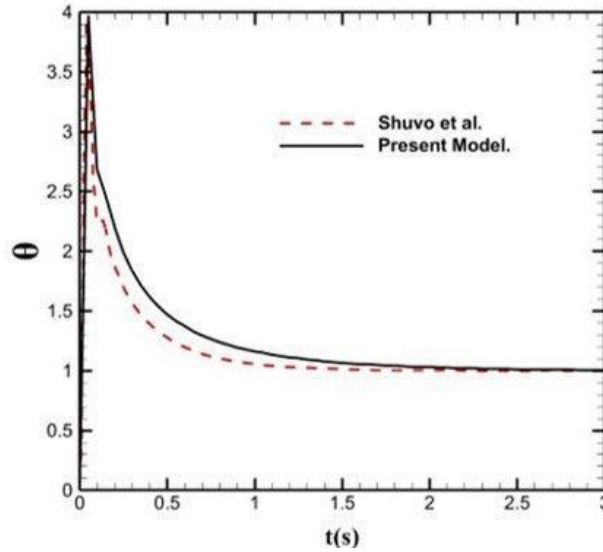


Fig. 3: Benchmarking of the obtained results from the current numerical model with Shuvo et al. (2022) in terms of Θ for $K_p = 0.01 \text{ ms}^{-1}\text{K}^{-1}$, $K_i = 0.1 \text{ ms}^{-2}\text{K}^{-1}$, and $K_d = 0.0001 \text{ mK}^{-1}$. (color online).

To validate the accuracy of the numerical model and the computational procedure described earlier, an examination of control flow and thermal transport within a vented square enclosure with a circular cylinder in a heated condition was conducted. The investigation utilized the study by Shuvo et al.[16] as a benchmark.

5. Result and Discussion

The present study focuses on determining the optimal parameters for P, PI, and PID controllers applied to thermal management within a square cavity hosting discretely heated cylinders, using Al_2O_3 -

water nanofluid as the cooling medium. The experimental setup involves two distinct cooling circuits: a constant cooling circuit and a variable cooling circuit. The PID control strategy is implemented to regulate the flow within the variable cooling circuit, aiming to maintain the temperature within the square cavity precisely at 300K. Initially, the controller is deactivated to observe the temperature response solely to the constant flow. Subsequent phases involve the application of a P controller with varying parameters ($K_p = 0.001, 0.002, \text{ and } 0.003 \text{ ms}^{-1}\text{K}^{-1}$), followed by the integration of a PI controller utilizing $K_p = 0.003 \text{ m/s.K}$ and varying K_i values ($0.015, 0.013, \text{ and } 0.011 \text{ m/s}^2\text{K}$). Finally, a PID controller is deployed, with fixed K_p (0.003 m/s.K) and K_i ($0.011 \text{ m/s}^2\text{K}$) values, while exploring different K_d values ($0.0005, 0.0003, \text{ and } 0.0001 \text{ m/K}$). A comprehensive portrayal of velocity magnitude and temperature plots depicting the temporal evolution of flow characteristics and thermal distribution within the nanofluid is presented. Furthermore, probe plots exhibit the dynamic response sensed in the system temporally for each of the types of controllers.

6.1 Performance of Constant Cooling Circuit:

The constant cooling circuit's inlets have a velocity of 0.0075 m/s that provides a constant flow of nanofluids coming at 290K over the heated cylinders. When the controlled inlets are closed, and the controller is turned on, the probe temperature is found to be rising rapidly. From Fig. 4, the probe temperature plot is shown. Even with the constant flow, the probe temperature rises to 314K and settles there at 2.1 seconds .

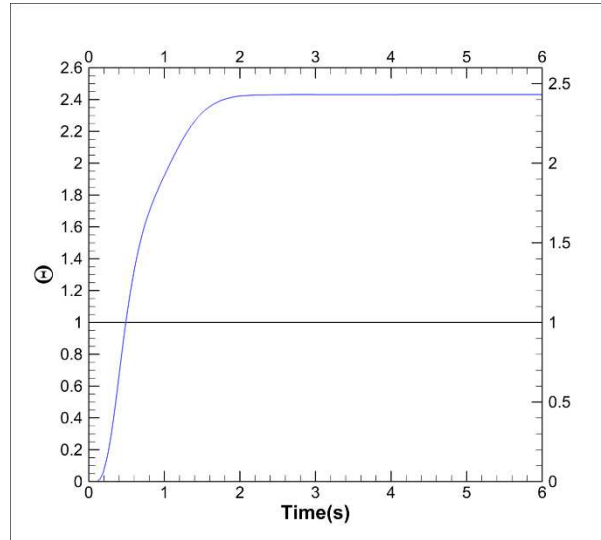


Fig. 4: Non-dimensional thermal (Θ) variations of the probe point with time for constant flow.

The iso-surface plot of the fluid temperature and velocity magnitudes, respectively, is presented in Figure 5. At $t = 0$ s, there is no flow and no temperature rise in the nanofluids. At $t = 1.25$ s, the temperature rises to 312 K, and the nanofluid flow is fully developed. At 2.1 seconds, the probe temperature settles at 314K.

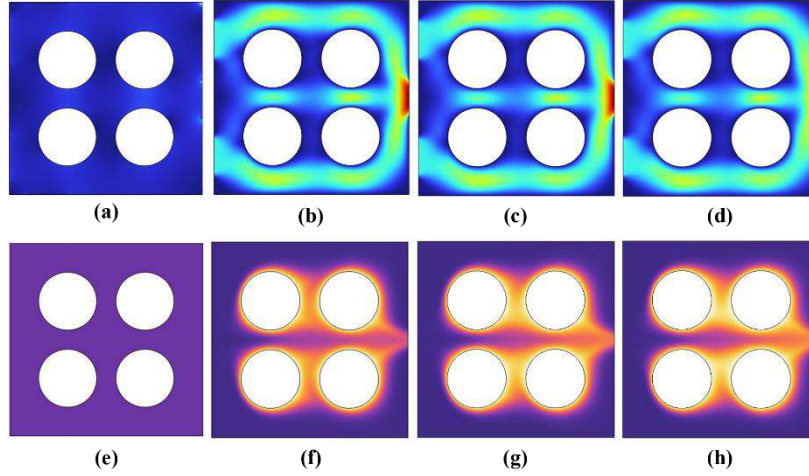


Fig 5: Isosurface plot of (a)-(d) streamlines and (e)-(h) temperature at (a), (e) $t = 0$ s, (b), (f) $t = 1.25$ s, (c), (g) $t = 2$ s, and (d), (h) $t = 6$ s during implementation of only constant cooling circuit with $u = 0.0075 \text{ ms}^{-1}$.

6.2 Response of P Controller

The implementation of a Proportional (P) controller represents a fundamental and straightforward approach in control systems design, offering a continuous output linked to the error detected by the feedback transducer. Despite its simplicity and directness, the P controller is limited in its ability to eradicate steady-state error, primarily due to its lack of consideration for the duration of the error's persistence. Considering a P controller, zero values are assigned to both K_i and K_d controllers. From Fig. 6, the probe plot with the P controller for $K_p = 0.001$, 0.002 , and $0.003 \text{ ms}^{-1}\text{K}^{-1}$ is observed. For lower values of K_p , there is less oscillation but a significantly higher overshoot, which is very undesirable. For $K_p = 0.003 \text{ m/s.K}$ the steady state error is at 0.06, which is much lower than the other two values of K_p . This expresses the trade-off between stability and accuracy. As the lowest amount of steady state error was found for $K_p = 0.003 \text{ m/s.K}$, this value was chosen for further studies.

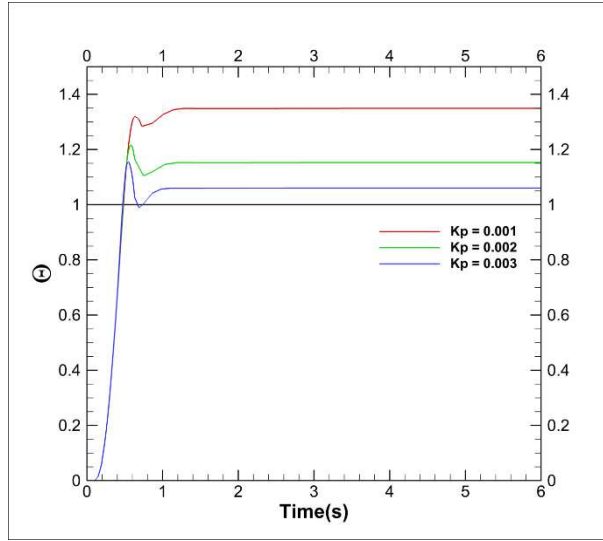


Fig. 6: Non-dimensional thermal (Θ) variations of the probe point with time for $K_p = 0.001$, 0.002 , and $0.003 \text{ ms}^{-1}\text{K}^{-1}$ at the time of using the P controller.

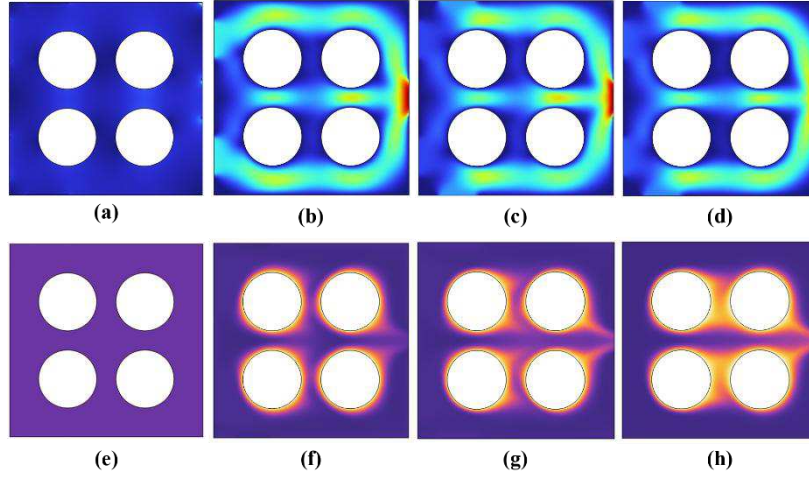


Fig 7: Isosurface plot of (a)-(d) streamlines and (e)-(h) temperature at (a), (e) $t = 0 \text{ s}$, (b), (f) $t = 0.4 \text{ s}$, (c), (g) $t = 0.57 \text{ s}$, and (e), (h) $t = 2 \text{ s}$ at the time of using the P controller with $K_p = 0.003 \text{ ms}^{-1}\text{K}^{-1}$.

For qualitative visualization, the temperature Fig. 06 and velocity magnitude plots (Fig.7) at $K_p = 0.003 \text{ m/s.K}$ are generated. At $t = 0 \text{ s}$, there is no flow in the cavity. The constant flow starts immediately, and the nano fluid adjacent to the heated cylinders begins to heat up. As soon as the probe temperature rises beyond the setpoint temperature, the controlled flow begins, triggered by the P controller. The controlled flow takes over the system fast and the temperature drops below the set point, which turns off the controlled flow again, making the temperature rise again. Thus, controlled flow was activated, and finally it steadied at 300.6 K .

6.3 Response of PI controller

The response of Proportional Integral (PI) controllers takes in the inputs of both an integral and proportional functions on the detected error by the feedback loop or transducer. The integral component of the feedback eliminates the steady state error, and the proportional component decreases the rise time. While keeping $K_p = 0.003$ constant, which provided the least steady state error in the P controller, three iterations were done for the values of $K_i = 0.011$, 0.013 , and $0.015 \text{ ms}^{-2}\text{K}^{-1}$. It was observed that the settling time decreased for higher values of K_i ; however, this decrease is insignificant and hence was not a parameter that affected the choice of K_i values. The best result was obtained for the value of $K_i = 0.011 \text{ ms}^{-2}\text{K}^{-1}$, with the least oscillations and yielded the least overshoot of 54.1% out of the three, and had a settling time of 1.895s and a rise time of 0.248s.

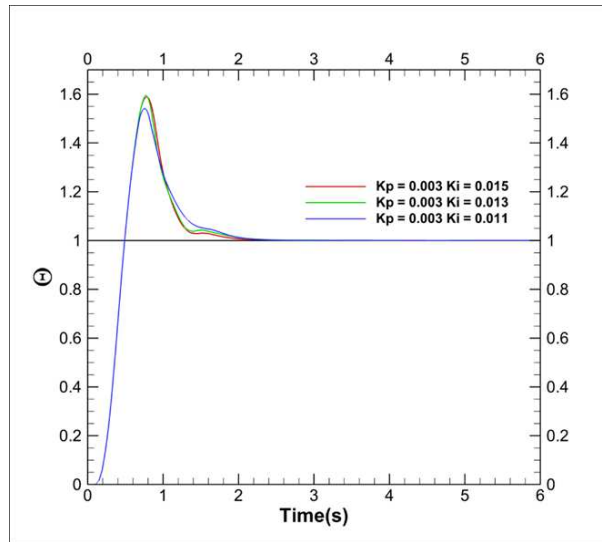


Fig.8: Non-dimensional thermal (Θ) variations of the probe point with time for $K_i = 0.011$, 0.013 , and $0.015 \text{ ms}^{-2}\text{K}^{-1}$ at the time of using the PI controller.

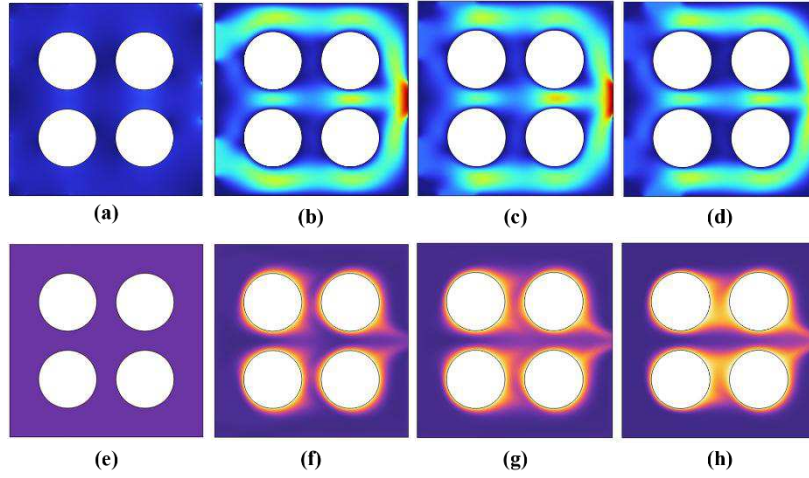


Fig. 9: Isosurface plot of (a)-(d) streamlines and (e)-(h) temperature at (a), (e) $t = 0$ s, (b), (f) $t = 0.5$ s, (c), (g) $t = 0.76$ s, and (d), (h) $t = 2$ s at the time of using the PI controller with $K_p = 0.003 \text{ ms}^{-1}\text{K}^{-1}$ and $K_i = 0.011 \text{ ms}^{-2}\text{K}^{-1}$.

For qualitative visualization, the temperature and velocity magnitude plots (Fig. 9) at $K_p = 0.003 \text{ m/s.K}$ and $K_i = 0.011 \text{ ms}^{-2}\text{K}^{-1}$ are generated. At $t = 0\text{s}$ (Fig 10), there is no flow in the cavity. The constant flow starts immediately, and the nano fluid adjacent to the heated cylinders begins to heat up. As soon as the probe temperature rises beyond the setpoint temperature, the controlled flow begins, triggered by the PI controller. Thus, controlled flow was activated, and the probe temperature steadied at 300K. The PI controller enables the flow to be controlled in such a way as to maintain the probe temperature constantly without any steady-state error.

6.4 Response of the PID controller

The Proportional Integral Differential (PID) controller adds a differential control action to the PI controller, which modifies the error feedback depending on the rate of change of the error. Thus, if the value of K_d is tuned correctly, it aids in decreasing the overshoot and oscillations in the system while having minimal effect on the rise time and settling time. The PID controller was tested for three values of $K_d = 0.0001, 0.0003$, and 0.0005 mK^{-1} while maintaining a constant value of $K_p = 0.003\text{ms}^{-1}\text{K}^{-1}$ and $K_i = 0.011\text{ms}^{-2}\text{K}^{-1}$ as carried forward from the analysis of the PI controller. The investigation revealed that for the value of $K_d = 0.0001 \text{ mK}^{-1}$, the slight oscillation in the system was further dampened, and the overshoot decreased to 52.4%, but the settling time slightly increased to 1.95s when compared to the PI controller while the rise time remained the same at a value of 0.248s.

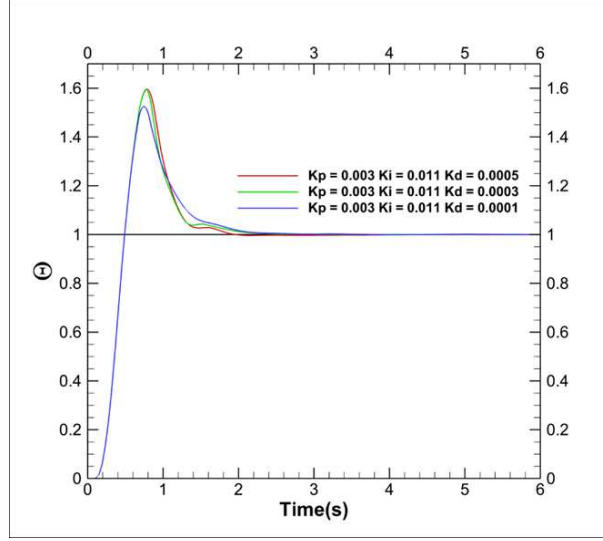


Fig.10: Non-dimensional thermal (Θ) variations of the probe point with time for $K_d = 5 \times 10^{-4}$, 3×10^{-4} , and 10^{-4} mK^{-1} at the time of using the PID controller.

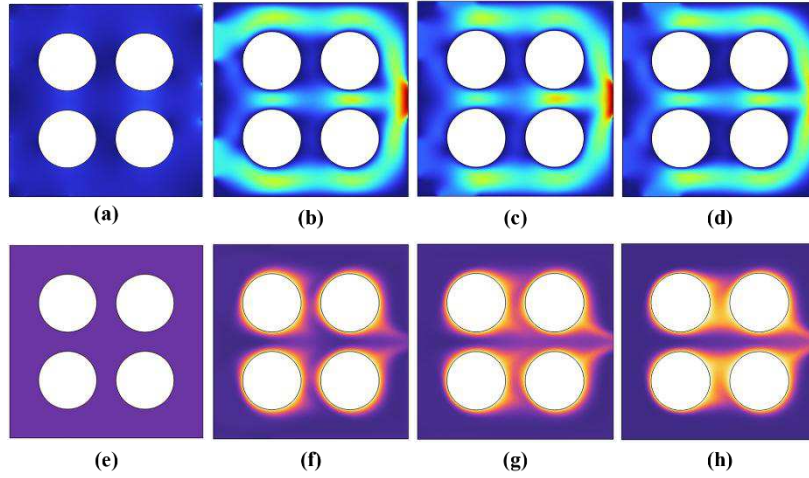


Fig. 11: Isosurface plot of (a)-(d) streamlines and (e)-(h) temperature at (a), (e) $t = 0 \text{ s}$, (b), (f) $t = 0.5 \text{ s}$, (c), (g) $t = 0.78 \text{ s}$, and (d), (h) $t = 2 \text{ s}$ at the time of using the PID controller with $K_p = 0.003 \text{ ms}^{-1}\text{K}^{-1}$, $K_i = 0.011 \text{ ms}^{-2}\text{K}^{-1}$, and $K_d = 10^{-4} \text{ mK}^{-1}$.

In terms of performance, it shows somewhat similar results to PI controllers. Similar isothermal and velocity contours are observed (Fig 11). The controlled flow starts once the domain gets warmer above the probe temperature, and the temperature becomes stable with the controlled flow after the settling time.

6. Conclusion

The study evaluates the impacts of regulations on the nanofluid flow controlled feedback controllers for managing the thermal performance within a vented enclosure. Based on the study, the concluding points are:

- The inclusion of a constant cooling circuit aids in decreasing the overshoot and rise time of the system as the flow allows the probe to sense the heated fluid more effectively, thus triggering the controller faster, and a constant cooling flow never lets the temperature rise uncontrollably.
- In the P controller, for higher values of K_p , the steady-state error decreases but cannot be reduced to zero.
- In the PI controller, there is no steady-state error; the settling time very slightly decreases with higher K_i values, but the offshoot increases significantly.
- In the PID controller, the best result was obtained, although any significant increase or decrease in the value of K_d leads to increased oscillations and overshoot.

Currently, there are no well-defined methods to tune non-linear systems like the present model. The trial-and-error method was used to tune this model. P, PI, and PID controllers were tuned in chronological order, carrying forward the value of the best result from each controller to the next controller for further analysis.

CRediT authorship contribution statement

Farheen Zaman : Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Ashfaq Raveed** : Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Aditto Arif Rahman** : Validation, Methodology, Formal analysis, Data curation. **Rafi Bin Dastagir** : Validation, Methodology, Formal analysis, Data curation. **Ummay Wajiha Tabassum** : Formal analysis, Data curation, Conceptualization.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data transparency

The authors declare that all data and materials as well as software application or custom code which support their published claims and comply with field standards.

Funding Declaration

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Data Availability

All data generated or analysed during this study are included in this published article. Additional simulation data and computational codes used during the current study are available from the corresponding author on reasonable request.

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