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Research Article

Stabilizing Taylor-Couette Flow via Temperature Gradients: Critical Thresholds and Heat Transfer Behavior at Various Radius Ratios

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ABSTRACT

This numerical analysis examines how a radial temperature gradient influences the stabilization threshold of Taylor-Couette flow across a range of radius ratios ($0.77 \leq \eta \leq 0.95$). Numerical simulations were conducted for seven radius ratios, with a constant temperature gradient applied between the inner and outer cylinders. Three-dimensional unsteady simulations were performed using the finite-volume method implemented in OpenFOAM to accurately resolve the temporal evolution and spatial structure of Taylor vortices under the imposed temperature gradients; pressure-velocity coupling was handled via the PISO algorithm, with second-order spatial discretization on a structured O-grid to ensure accurate capture of flow instabilities. The primary objective was to determine the temperature gradient required to stabilize the flow at the threshold of transition from laminar to vortex flow. Velocity contours, vorticity, skin friction coefficient, velocity profiles, and streamlines were analyzed to assess flow stability. The results reveal that the minimum stabilizing temperature gradient occurs at a radius ratio of 0.877, beyond which the required temperature gradient increases significantly. For a radius ratio of 0.77, the Richardson number exceeds 10, leading to flow destabilization due to buoyancy forces. A predictive relationship for the stabilizing temperature gradient as a function of the radius ratio was derived. Additionally, the Nusselt number at the stabilizing temperature gradient was examined, and empirical correlations were provided. The findings highlight the critical role of temperature gradients in controlling flow stability and vortex suppression in Taylor-Couette systems, offering valuable insights for engineering applications.

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1. Introduction

The Taylor-Couette flow, characterized by the movement of a viscous fluid between two

concentric rotating cylinders, provides a rich field for study in fluid dynamics due to its complex behavior and wide-ranging applications in engineering and natural systems. The

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interaction between rotation and shear leads to the formation of various flow regimes, from laminar to turbulent, which are influenced by parameters such as the Reynolds number and the geometry of the system.

The transition from laminar flow to Taylor vortex flow can lead to detrimental conditions. One such condition is the increase in frictional stresses on the cylinder, accompanied by very high peaks that can cause noise and erosion on the cylinders. Additionally, the formation of Taylor vortices can enhance transfer processes, including mass transfer, heat transfer, and momentum transfer, which may be undesirable in some instances.

In the flow between two enclosed cylinders, a wide range of flow states, from laminar to fully turbulent, can occur after the initial transition to Taylor vortex flow. The first critical Taylor number for the formation of Taylor vortices depends on many factors, including the rotation speed of the cylinders, the radius ratio of the two cylinders, the aspect ratio, and the Reynolds number of the flow.

To delay the formation of Taylor vortices, researchers have numerically and experimentally investigated three different methods. These three methods include adding axial flow to Taylor-Couette flow [1-2], applying a temperature gradient between the inner and outer cylinders [3], and creating roughness on one or both cylinders [4].

In recent years, the introduction of thermal gradients, especially temperature gradients in the radial direction, has attracted considerable attention as this adds more complexities to the dynamics of flow. The presence of a temperature gradient in the radial direction not only alters the viscosity of the fluid but also affects stability and flow transition thresholds. This phenomenon is particularly significant in industrial processes where temperature variations are common, such as in chemical reactors, heat exchangers, and cooling systems. Understanding the impact of these thermal effects on Taylor-Couette flow is essential for optimizing performance and ensuring operational efficiency. Studies indicate that the transition from base laminar flow to helical patterns in the axial direction depends on the temperature gradient ΔT . [5-7]

Chen and Kuo [8] studied the linear stability of stable circular Couette flow with a small radial temperature gradient in 1990. They assumed the outer cylinder is stationary while the inner cylinder is rotating, considering the interaction of the radial temperature gradient with gravitational and centrifugal forces in their stability formulation. They found that the critical Reynolds number depends on the ratios of

centrifugal and gravitational potentials, Prandtl number, and the temperature gradient between the cylinders. They also concluded that at low Prandtl numbers, thermal disturbances are not significant, and energy is mainly transferred from base flow to disturbances; however, at high Prandtl numbers, the kinetic energy of disturbances exceeds the potential energy associated with buoyancy.

Ali [9] investigated asymmetric states of the effect of temperature gradient on Couette flow stability. The stability equations were numerically solved for thin gap cases considering asymmetric disturbances. They showed that for cylinders with different rotation directions, critical asymmetric disturbances become axially symmetric when the outer cylinder temperature (T_2) exceeds the inner cylinder temperature (T_1) by a specific critical amount. For a stationary outer cylinder, when T_2 is lower than T_1 by a specific critical amount, symmetric disturbances become asymmetric.

Kang et al. [10] numerically examined the effect of radial temperature gradient on Taylor-Couette flow. They detailed the temperature and flow field concerning variations in Grashof number and demonstrated that spiral vortices are generated with an increasing temperature gradient. They classified flow patterns for different Grashof numbers based on flow field characteristics and spiral vortices. They concluded that the correlation between Richardson number and wave number indicates that as Richardson number increases, both the angle and size of spiral vortices increase.

Liu et al. [11] studied the flow between two concentric cylinders with the inner cylinder rotating and a radial temperature gradient applied using the digital particle image velocimetry (PIV) method. They investigated the flow transfer process under both positive and negative temperature gradients with four different models of a stationary outer cylinder, with varying numbers of gaps (6, 9, and 18). They demonstrated that when the rotational Reynolds number is small, the buoyancy force due to the temperature gradient clearly creates a spiral flow. For the simple model with 6 gaps, the transition to turbulent Taylor vortex flow was not affected by the temperature gradient considered in this study. Furthermore, the transition process for models with more gaps (9 and 18 gaps) was accelerated due to the presence of gap walls, and as the temperature gradient increased, the critical Reynolds number for the transition process decreased. They also stated that as the Reynolds number increases, the instability caused by inertia surpasses the buoyancy effect.

Viazzo and Poncet [12] numerically examined the stability of flow in a Taylor-Couette system subjected to a temperature gradient. They indicated that the reason for the formation of instabilities is the intense competition between an angular flow caused by rotation and an axial flow due to convection. They reported seven different flow patterns that appear as spiral rolls, wave vortices, or combinations of both, depending on the Taylor and Rayleigh numbers. The spatial-temporal characteristics of these flow patterns were investigated with good agreement concerning the main features of spiral regimes near the initial instability threshold. Finally, correlations for average Nusselt numbers along both walls were presented in relation to the Taylor number.

Tuliszka-Sznitko and Kiełczewski [13] studied the numerical Taylor-Couette flow with an applied temperature gradient in a cavity with an aspect ratio of $\Gamma = 3.76$ and radius ratios of $\eta = 0.375$ and $\eta = 0.82$. They analyzed the impact of boundary conditions at the end wall and thermal conditions on the flow structure and on the distribution of Nusselt number and torque along the inner and outer cylinders. For the case of $\eta = 0.375$, they showed that at a Reynolds number of 80, the Taylor-Couette flow structure is three-cellular, which transitions to a single-cellular structure as the Reynolds number increases to 270 due to the growth of adjacent vortices from the rotating end disk, ultimately becoming a one-cell structure at Reynolds number 281. The flow structure was also demonstrated for a Rossby number of 0.1.

Deka and Gupta [14] investigated how a radial temperature gradient and an axial magnetic field influence the stability threshold of Taylor-Couette flow. Their model involved an incompressible, electrically conducting fluid confined between concentric cylinders. By solving the derived disturbance equations numerically under the assumption of a small magnetic Prandtl number, they found an apparent stabilizing effect from the magnetic field: the critical Taylor number required for the onset of instability rose with the Hartmann number. Furthermore, their results indicated that systems with insulating walls were more prone to instability than those with conducting walls, and that a higher heat flux consistently lowered the critical Taylor number.

Kirillov and Mutabazi [15] employed a short-wavelength approximation to analyze the local stability of circular Couette flow under a radial temperature gradient, where centrifugal forces induce buoyancy in the absence of natural gravity. Their linearized analysis revealed that this centrifugal buoyancy significantly modifies the instability dynamics. For flows that are

already unstable according to the Rayleigh criterion, inward heating was found to intensify the instability. Conversely, outward heating prompted the emergence of oscillatory modes. Notably, they also demonstrated that inward heating can destabilize otherwise stable Rayleigh flows, triggering steady instabilities at high Prandtl numbers and oscillatory ones at low Prandtl numbers.

Zhu et al. [16] systematically evaluated the impact of gap wall aspect ratios on the thermohydrodynamic performance of Taylor-Couette flow. Through a comparative study of four geometric models, their findings revealed that a specific aspect ratio of 0.75 achieved superior heat transfer performance, as measured by the Nusselt number. This performance peak was notable, as further enlargement of the aspect ratio did not lead to significant enhancement. The study also reported that the heat transfer rate for this optimal geometry was reinforced at higher Reynolds numbers. Furthermore, they noted that the temperature gradient has a suppressive effect on the transition from laminar Couette flow to Taylor vortex flow, and this effect becomes more pronounced with increasing temperature gradient. Finally, empirical formulas were derived for modeling with an aspect ratio of 0.75 under various conditions.

Khawar et al. [17] investigated counter-rotating Taylor-Couette flow with a radial temperature gradient and a radius ratio of 0.5 ($\eta = 0.5$). They considered a constant angular velocity but in opposite directions for both the inner and outer cylinders in various cases. Direct numerical simulations (DNS) were conducted for Reynolds numbers ranging from 1000 to 5000 and Richardson numbers from 0 to 0.4. The analysis focused on how these parameters influence the near-wall flow and the formation of coherent structures. In cases where buoyancy is neutral, coherent structures near the wall exist close to both the inner and outer walls, with a core that is almost vortex-free. As the Richardson number increases, more compact and finer vortical structures spread only in half of the circumferential domain within the core. This behavior is attributed to stable or unstable spatial classification in the azimuthal direction, leading to turbulence generation in the lower half of the domain and reduced turbulence in the upper half. Additionally, they showed that heating the outer cylinder wall leads to increased turbulence, while heating the inner cylinder wall results in a slight reduction in surface friction of the inner cylinder.

Despite previous studies addressing thermal effects in Taylor-Couette systems, a systematic investigation of the simultaneous influence of radius ratio and radial temperature gradient on

the re-laminarization threshold at the first critical Taylor number remains lacking. The present study addresses this gap. The main objectives and novel contributions are:

- To perform a systematic numerical investigation of the combined effects of radius ratio ($0.77 \leq \eta \leq 0.95$) and radial temperature gradient on flow stability at the first critical Taylor number.
- Determining, for the first time, the minimum temperature difference required for complete re-laminarization as a function of radius ratio.
- To identify the optimal radius ratio corresponding to the lowest stabilizing thermal energy requirement.
- Establishing a predictive correlation that links the stabilizing temperature gradient to the radius ratio.
- To quantify the associated heat transfer behavior and develop empirical correlations for the Nusselt numbers at the stabilization threshold.
- Evaluating the impact of vortex suppression on the skin friction coefficient and demonstrating its reduction due to thermal stabilization.

2. Numerical Information

2.1. Geometrical Configuration, Boundary Conditions and Important Parameters

As shown in Fig. 1, the computational domain represents a Taylor-Couette apparatus, defined by two concentric cylinders. The inner cylinder, with radius R_i , rotates at a constant angular velocity Ω , while the outer cylinder of radius R_o is stationary. The radius ratio, defined as $\eta = R_i/R_o$, was varied across seven cases within the range of $0.77 \leq \eta \leq 0.95$. The gap width between the cylinders, a critical parameter, is given by $d = R_o - R_i$. L denotes the axial dimension of the domain and is equal to 450 mm. The temperatures of the inner and outer cylinders are denoted as T_i and T_o , respectively. Two other key parameters in this problem are the curvature parameter, defined as $\delta = d/R_i$, and the aspect ratio, given by $\Gamma = L/d$.

The boundary conditions for the upper and lower plate of the cylinder are considered as no-slip walls with zero velocity, and adiabatic temperature conditions are applied. Furthermore, the inner cylinder is subjected to no-slip wall conditions and a constant rotational speed, along with a fixed temperature condition. The outer cylinder is subject to no-slip wall

boundary conditions with zero velocity and a fixed temperature condition.

In the presence of a radial temperature gradient, four key dimensionless parameters significantly influence Taylor-Couette flow.

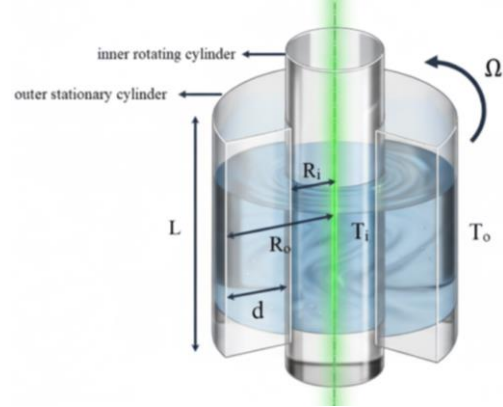


Fig. 1. Geometrical configuration and boundary conditions

These parameters are the rotational Reynolds number, Taylor number, Grashof number, and Nusselt number, which are defined as follows.

$$Re = \frac{\Omega d R_i}{\nu} \quad (1)$$

$$Ta = \frac{\Omega^2 R_i}{\nu^2} \left(\frac{d}{2}\right)^3 \quad (2)$$

$$Gr = \frac{g \beta (T_o - T_i) d^3}{\nu} \quad (3)$$

$$Nu = \frac{q(R_o - R_i)}{(T_w - T_b)k}, \quad \overline{Nu} = (\sum_{i=0}^{10} (Nu \Delta z)_i) / L \quad (4)$$

The flow patterns and heat transfer in rotating annular channels are influenced by the Taylor number (Ta) and the Grashof number (Gr). The Grashof number represents the ratio of buoyancy forces to viscous forces, governing the flow regime within fluid boundary layers in laminar systems. Correlation 4 defines both the local and average Nusselt numbers, with thermal conductivity (k) determined by the local bulk temperature (T_b).

Taylor's seminal work [18] established the first critical rotational speed threshold, demarcating the transition from laminar to turbulent flow. According to this definition, Sobolik et al. [19] established the first critical Taylor and Reynolds numbers in relation to the radius ratio of the two cylinders when no axial flow is present, as expressed in Eqs. (5) and (6).

Their findings indicated that the first critical Taylor number is determined exclusively by the radius ratio and remains unaffected by the rotational speed or the absolute dimensions of the cylinders [19].

$$Ta_{cr1} = 36.2(\eta - 0.256)^{-0.445} \quad (5)$$

$$Re_{cr1} = \frac{Ta_{cr1}}{\sqrt{\delta}} \quad (6)$$

2.2. Governing Equations

For the numerical simulation of this problem, the flow is considered to be laminar, incompressible, and Newtonian. Therefore, the continuity and momentum equations are used as follows:

$$\nabla \cdot \vec{V} = 0 \quad (7)$$

$$\rho \left(\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} \right) = -\nabla p + \mu \nabla \cdot (\nabla \vec{V} + \nabla \vec{V}^T) \quad (8)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\vec{V} \cdot \nabla) T \right) = k \nabla^2 T + \phi \quad (9)$$

where V , p , C_p and ρ represent velocity, pressure, specific heat capacity and density, respectively.

All simulations were performed using a three-dimensional and transient numerical approach in order to accurately capture the evolution and suppression of Taylor vortices.

2.3. Discretization and Grid strategy

This study utilizes the OpenFOAM open-source code for numerical simulations based on a structured O-grid. The grid employs a hexagonal structure in the radial, azimuthal, and axial directions and features local refinement near the cylinder walls.

The PISO method is employed to couple the continuity and momentum equations. Furthermore, a second-order discretization scheme is used for the viscosity terms. In the transient analysis, a convergence tolerance of 10^{-4} was applied at each time step. The analysis was conducted with multiple time step sizes, culminating in the selection of a 0.002 second time step.

Water serves as the working fluid, with density variations modeled using the Boussinesq approximation. Consequently, water's thermophysical properties change according to the temperature differential.

To resolve boundary layer effects, the computational grid adopts a structured O-grid topology, with increased mesh density adjacent to the cylinder surfaces. (Fig. 2)

Grid independence was confirmed by analyzing four distinct meshes with cell counts varying between 79,800 and 750,000. To validate the numerical setup, the critical Taylor numbers for the transition from laminar flow to Taylor vortex flow (TVF) and from TVF to wavy vortex flow (WVF) were calculated and compared with [19] and [20].

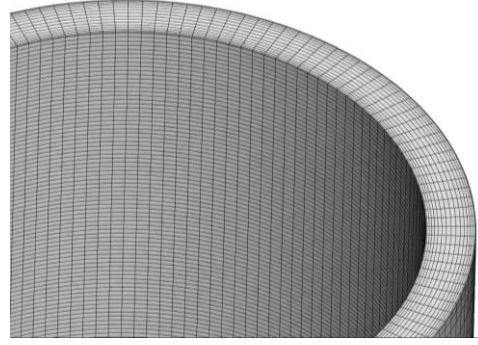


Fig. 2. Computational mesh used in the simulations, showing the structured O-grid topology and mesh refinement near the cylinder walls (Adapted from [2])

The results indicate that the maximum simulation error in estimating the first critical Taylor number is about 1%, while for the second critical Taylor number, it is 4.4%. As the grid independence study and numerical validation are comprehensively addressed by Charmiyan et al., [2], we omit their repetition in this paper.

3. Results and Discussion

3.1. Evaluation of Critical Re-laminarization Temperature Gradients for Diverse Radius Ratios

As mentioned earlier, one way to stabilize Taylor-Couette flow at the first critical Taylor number (Ta_{cr1}) is to establish a specific temperature difference between the inner and outer cylinders.

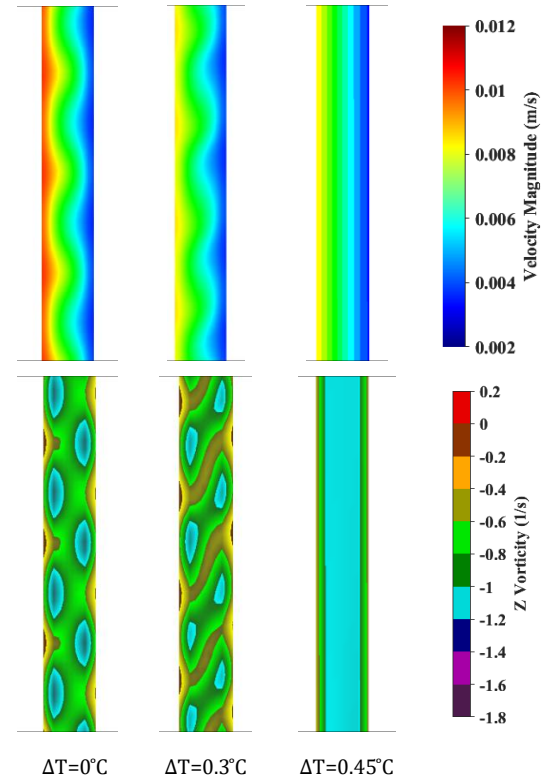


Fig. 3. (up) Velocity magnitude (m/s) and vorticity contours (1/s) (down) for different temperature gradient ($\eta=0.877$, $Ta=44.75$)

This section presents simulations conducted at Tacr1 for various radius ratios ($0.77 < \eta < 0.95$), where the inner cylinder's rotational speed is calculated via Equation (6). The investigation proceeds by imposing incremental thermal differences between the cylinders, analyzing Taylor-Couette instability evolution via velocity magnitude and vorticity distributions. The stabilization criterion $\Delta T_{\text{re-lam}}$ is determined for each η as the minimum temperature gradient required to achieve complete re-laminarization of the flow field.

The effects of temperature variation on flow characteristics are illustrated in fig. 3 through velocity and vorticity contours at $\eta = 0.877$, selected to demonstrate key trends without showing similar patterns for other radius ratios.

Figure 3 demonstrates that in the absence of thermal gradients ($\Delta T=0^\circ\text{C}$), well-defined Taylor vortices occupy the entire flow domain. With increasing temperature difference ($\Delta T=0.3^\circ\text{C}$), axial flow development induces vortex stretching. At $\Delta T=0.45^\circ\text{C}$, thermal forces overcome rotational effects, leading to complete vortex suppression - a threshold defined as the re-laminarization temperature gradient.

Figure 4 reveals the fundamental transformation from helical to purely axial streamlines, providing visual confirmation that the applied thermal gradient has successfully suppressed all Taylor vortices. This streamline rectification serves as direct evidence of flow stabilization.

Below a critical radius ratio ($\eta < 0.77$), increasing the thermal gradient fails to stabilize the flow. This behavior is investigated through simulations of six temperature gradients (0- 3°C), with analysis of velocity fields, vorticity distributions, and streamline patterns.

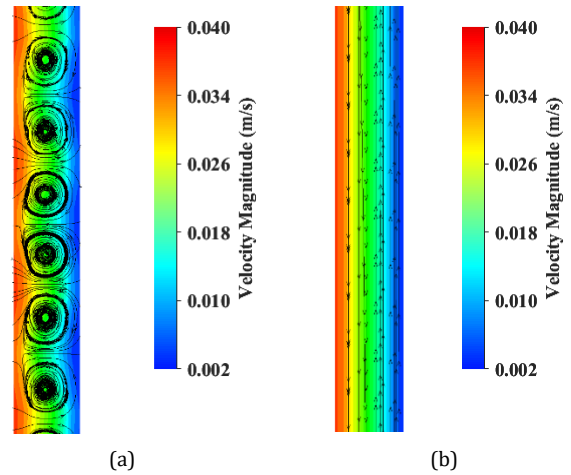
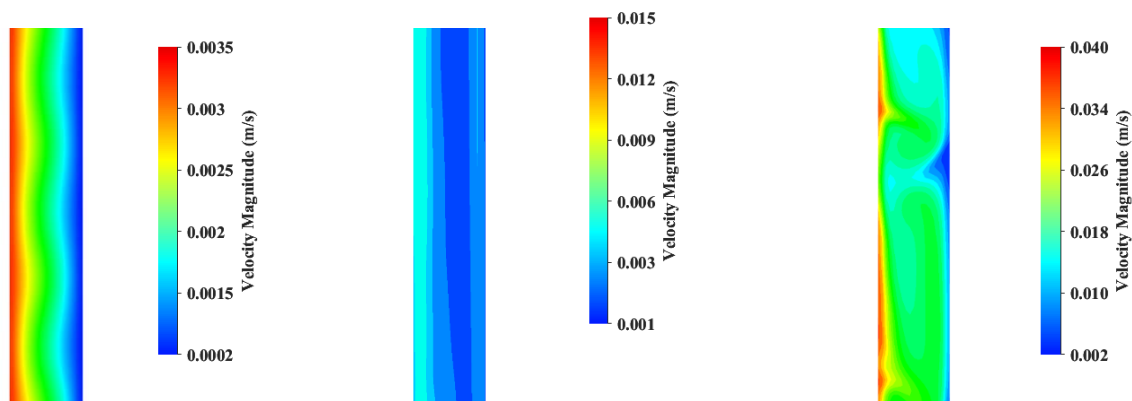


Fig. 4. streamlines and velocity magnitude (m/s) contours for a) isothermal case ($\Delta T=0^\circ\text{C}$); b) stabilized flow at $\Delta T=0.45^\circ\text{C}$ ($\eta=0.877$, $Ta=44.75$)

As shown in Fig. 5, up to $\Delta T=2^\circ\text{C}$, the vortices decrease but do not disappear. As the temperature difference increases to 3°C , the vortices increase and take on more complex shapes. The reason for this is that as the distance between the two cylinders increases, the influence of the cylinder walls decreases, and buoyancy forces play a greater role in flow instability. In this case, the Richardson number is 18.84. Deka and Gupta [14] showed that when the Richardson number exceeds 10, it has a significant effect on flow instability.

In Fig. 6, the streamlines are plotted for three temperature differences. At a temperature difference of 2°C , compared to isothermal case, most vortices disappear, and only one large vortex is formed in the study area. However, when the temperature gradients is increased to 3°C , new vortices with different structures are formed, indicating the re-emergence of flow instability.



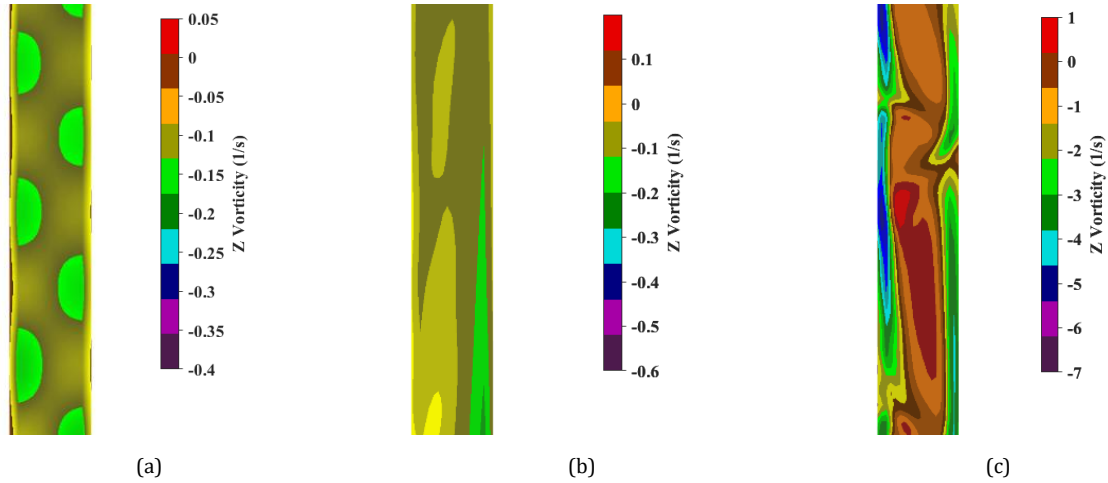


Fig. 5. The effect of thermal gradient between the inner and outer cylinders on vortex suppression at $\eta=0.77$.
a) $\Delta T=0^\circ\text{C}$, b) $\Delta T=2^\circ\text{C}$ and c) $\Delta T=3^\circ\text{C}$

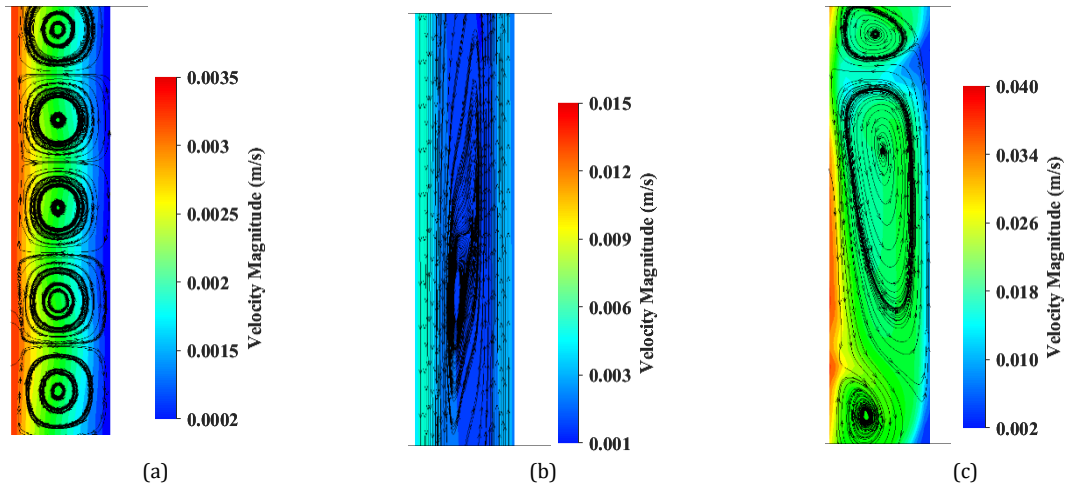


Fig. 6. Streamlines and velocity magnitude (m/s) at different thermal gradient between the inner and outer cylinders at $\eta=0.77$.
a) $\Delta T=0^\circ\text{C}$; b) $\Delta T=2^\circ\text{C}$; c) $\Delta T=3^\circ\text{C}$

3.2. Effect of Temperature on Taylor Vortices

Figure 7 illustrates the streamline patterns for three distinct temperature differentials applied to the concentric cylinders at a radius ratio (η) of 0.95. Under isothermal conditions, the vortex pair exhibits a characteristic length of 8.65 mm.

When a thermal gradient of $\Delta T = 1.2^\circ\text{C}$ is imposed, the vortex pair elongates to 10.05 mm. A further increase in the temperature gradient to $\Delta T = 2^\circ\text{C}$ results in a pronounced expansion of the vortical structure, reaching 20.17 mm.

The reason for this is that as the temperature gradient increases, axial flow forms and

gradually stretches the vortices, causing some vortices to disappear. As the temperature gradient between the two cylinders increases further, the length of the vortices increases significantly, eventually leading to the elimination of the vortices.

Figure 8 displays velocity profiles in the meridional plane (at $z=L/2$) for $\eta=0.925$ under three thermal conditions. While $\Delta T=0^\circ\text{C}$ and 1.2°C exhibit characteristic nonlinear profiles, the $\Delta T=1.5^\circ\text{C}$ case shows a perfectly linear distribution, confirming complete vortex suppression.

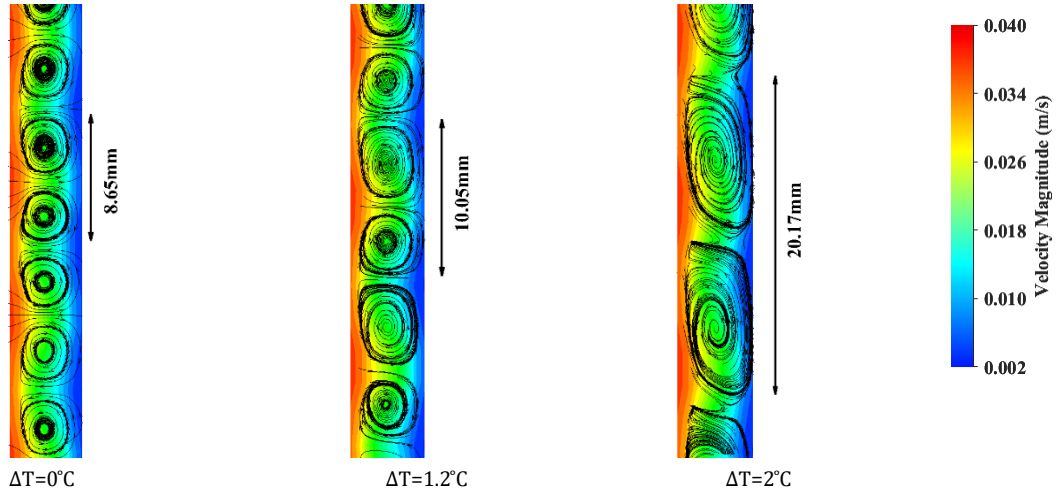


Fig. 7. Length of Taylor vortex pairs at different temperature gradients between the inner and outer cylinders at $\eta=0.95$

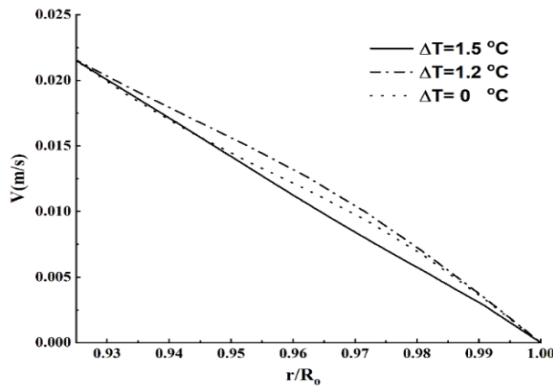


Fig. 8. Velocity profile for different temperature gradients between the inner and outer cylinders at $\eta=0.925$

As mentioned earlier, for a radius ratio of 0.77, since the Richardson number exceeds 10, buoyancy forces destabilize the flow, and thus no stabilizing temperature gradient is shown in Fig. 9 (a) for this radius ratio.

To predict the temperature gradient required to eliminate Taylor vortices at the first critical Taylor number, curve fitting is used, and a second-order curve is obtained. As shown in Fig. 9a, the stabilizing temperature difference can be calculated for different radius ratios using the following relation.

$$\Delta T = 523.3\eta^2 - 912.5\eta + 398.3 \quad (10)$$

The stabilizing temperature difference ΔT_{re-lam} as a function of radius ratio η is well represented by the second-order correlation given in Equation (10).

The goodness-of-fit is quantified by $R^2=0.9106$, $RMSE= 0.35$ °C, and $MAE= 0.30$ °C, confirming that the proposed relation provides a reliable engineering estimate of the minimum temperature gradient required for complete re-laminarization.

3.3. The Role of Radius Ratio in Determining the Stabilizing Temperature Gradient

Figure 9a presents the relationship between the critical re-laminarization temperature difference (ΔT_{re-lam}) and radius ratio (η). The data reveal a non-monotonic trend, with ΔT_{re-lam} decreasing until $\eta=0.877$ (minimum stabilization threshold) before increasing sharply at higher radius ratios. This optimal geometry ($\eta=0.877$) represents the most energy-efficient configuration for vortex suppression in engineering applications. This value can be used in engineering designs where the elimination of Taylor vortices at the onset of their formation is required.

To understand the reason for this, it should be noted that we are seeking the stabilizing temperature gradient at the first critical Taylor number.

The first critical Taylor number, which determines the rotational flow velocity between the two cylinders, is derived from the relation 5. If we plot the rotational velocity of the inner cylinder as a function of the radius ratio at the first critical Taylor number using this relation, we observe that the rotational velocity required to form vortices increases slowly up to a radius ratio of 0.877, but beyond this, the required rotational velocity increases sharply (Fig. 9b). Therefore, up to a radius ratio of 0.877, the rotational velocity is low, and the ratio of rotational to axial forces is small. Thus, from a radius ratio of 0.77 to 0.877, as the distance between the two cylinders decreases, the required temperature gradient for flow stabilization also decreases.

However, beyond a radius ratio of 0.877, with the sudden increase in rotational velocity, the rotational forces increase sharply, causing severe flow instability, and thus the required temperature gradient for flow stabilization also increases significantly.

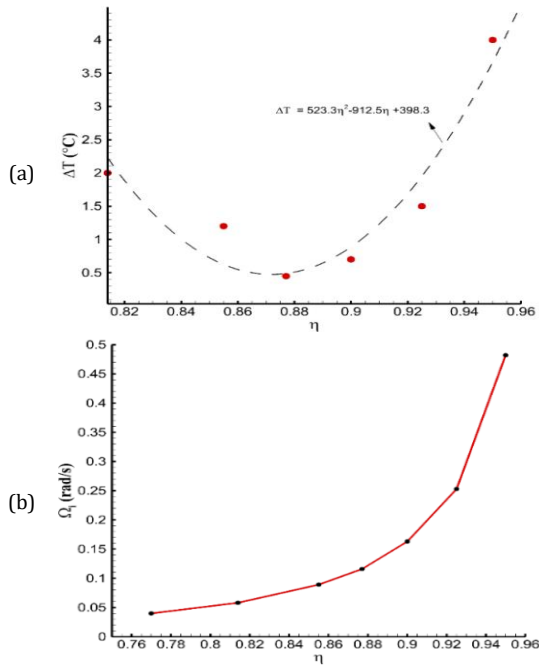


Fig. 9. (a) Stabilizing temperature gradient at different radius ratios; (b) the required rotational velocity of the inner cylinder to reach the first critical flow at different radius ratios

3.4. Variation in Skin Friction Coefficient in the Presence of a Temperature Gradient

A key objective in suppressing Taylor vortices and preventing flow instability is to reduce the skin friction on the cylinders and prevent the effects of high friction values. Figure 10 shows the variation of the skin friction coefficient on the inner cylinder for a radius ratio of 0.95 and in the presence of a temperature gradient over the first quarter of the cylinder length. As can be seen, when there is no temperature gradient, the range of skin friction coefficient oscillations is between 0.013 and 0.027.

As the temperature gradient increases, the oscillation range gradually decreases, so that at a temperature difference of 3°C, the average maximum range decreases to 0.023. As the temperature difference increases and the vortices disappear, the skin friction oscillations disappear, and the skin friction coefficient reaches a value of 0.016, which is a 30% reduction compared to the maximum values without a temperature gradient.

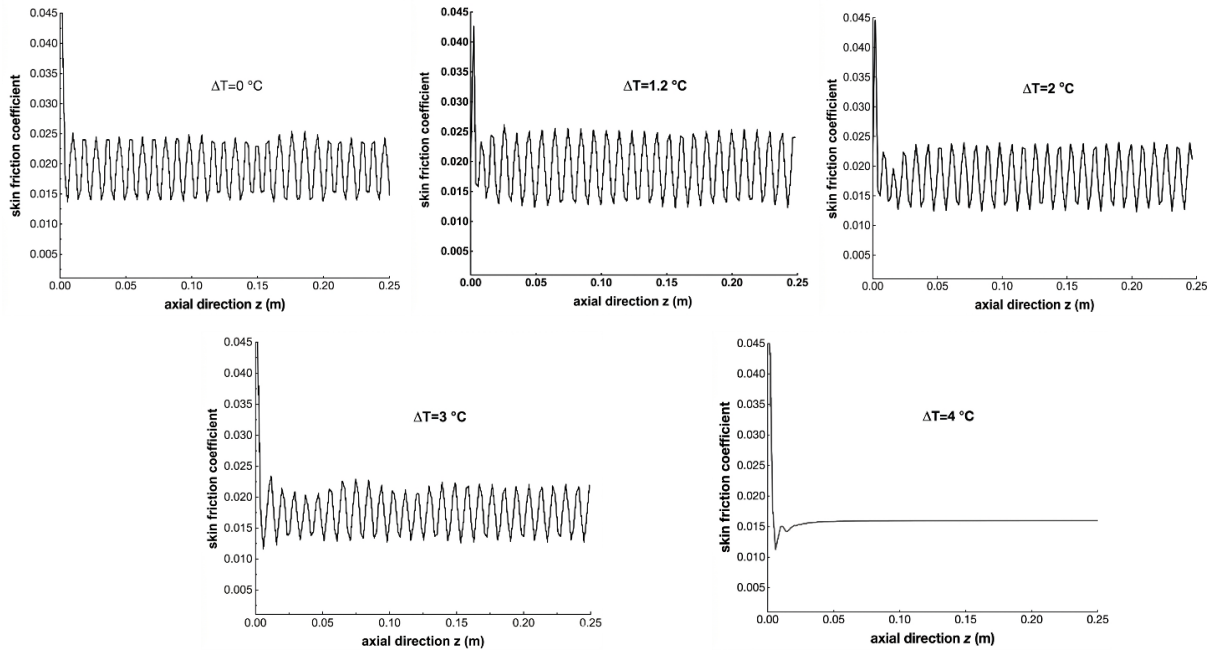


Fig. 10. Variation of the skin friction coefficient at different temperature gradients at $\eta = 0.95$

3.5. Determination of the Nusselt numbers for both inner and outer cylinders under ΔT_{re-lam}

Table 1 presents the key parameters of the problem for seven different radius ratios investigated in this study. These seven parameters include: ΔT_{re-lam} , Grashof number, Richardson number, first critical Taylor and Reynolds numbers, and the corresponding average Nusselt numbers for both the inner and outer cylinder walls.

Thus, as the radius ratio decreases, the Nusselt number on the outer and inner cylinders increases. As can be seen, the Nusselt number for the two radius ratios $\eta = 0.814$ and $\eta = 0.855$ is higher compared to the other radius ratios. The reason for this could be the larger Grashof number at these two radius ratios, and since the Grashof number is the ratio of buoyancy force to viscous force, the buoyancy force increases at these two radius ratios, resulting in stronger secondary velocities, which enhance convective

heat transfer and thus increase the average Nusselt number.

An empirical formula can be derived from the obtained data points for the Nusselt numbers as follows:

$$\begin{aligned} Nu_i &= \begin{cases} Gr^{0.155} & Gr < 10661 \\ Gr^{0.165} \times Ri^{0.1} & Gr \geq 10661 \end{cases} \\ Nu_o &= \begin{cases} Gr^{0.055} & Gr < 10661 \\ Gr^{0.12} \times Ri^{0.25} & Gr \geq 10661 \end{cases} \end{aligned} \quad (11)$$

Table 1. Important parameters for the inner and outer cylinders at the stabilizing temperature gradient and other variables

η	0.95	0.925	0.9	0.87	0.855	0.814	0.77
ΔT_{re-lam}	4	1.5	0.7	0.45	1.2	2	-
Gr	1190.89	1516.29	1725.63	2188.14	10661.92	44599.54	149602
Ri	0.034	0.0661	0.0989	0.1533	0.874	4.62	18.84
Ta_{cr1}	42.58	43.29	44	44.75	45.5	46.9	48.68
Re_{cr1}	185.6	152	132.1	116.3	110.4	97.2	89
Nu_i	2.98	3.02	3.11	3.28	4.66	6.51	-
Nu_o	1.47	1.49	1.52	1.6	2.95	5.32	-

4. Conclusions

The present numerical study systematically investigated the stabilizing effect of a radial temperature gradient on Taylor-Couette flow at the first critical Taylor number across a wide range of radius ratios ($0.814 \leq \eta \leq 0.95$). The principal findings are summarized as follows:

- The minimum temperature gradient required for complete re-laminarization (ΔT_{re-lam}) exhibits a non-monotonic dependence on the radius ratio η . The lowest stabilizing thermal gradient occurs at $\eta \approx 0.877$, making this geometry the most energy-efficient configuration for vortex suppression.
- For radius ratios $\eta < 0.814$, buoyancy forces become dominant (Richardson number > 10), and increasing the temperature gradient fails to stabilize the flow and may even intensify instability.
- As the imposed temperature gradient increases, Taylor vortices are progressively stretched axially, their length grows significantly, and they are ultimately fully suppressed once the critical re-laminarization threshold ΔT_{re-lam} is reached. This transition is accompanied by a change from helical to purely axial streamlines.
- A robust second-order correlation has been developed that accurately predicts the stabilizing temperature difference as a function of radius ratio:

$$\Delta T = 523.3\eta^2 - 912.5\eta + 398.3$$

(with $R^2 = 0.9106$, RMSE = 0.35 °C)

- Stabilization through the radial temperature difference reduces skin-friction coefficient fluctuations on the inner cylinder and lowers its average value by up to 30% compared to the isothermal case, which is beneficial for reducing noise, erosion, and energy losses.
- The average Nusselt numbers on both inner and outer cylinders increase as the radius ratio decreases, primarily due to the enhancement of buoyancy-driven secondary flows (higher Grashof numbers). Empirical correlations relating Nu to Gr have been proposed for engineering applications.
- The optimal radius ratio $\eta \approx 0.877$ simultaneously provides the lowest required stabilizing temperature gradient and effective heat transfer characteristics, offering valuable guidance for the design of rotating machinery, heat exchangers, and chemical reactors where control of Taylor vortices is desired.

These results demonstrate that a carefully chosen radial temperature gradient can serve as an efficient passive control strategy for delaying or eliminating Taylor vortex formation with minimal additional energy input.

Nomenclature

Gr	Grashof number
k	Thermal conductivity
L	Length [m]
Nu	Nusselt number

p	Pressure [N/m ²]
R	Cylinder radius [m]
Re	Rotational Reynolds number
Ri	Richardson number
T	Temperature [°C]
Ta	Taylor number
V	Velocity [m/s]

Greek symbol

β	Thermal expansion coefficient, 1/K
η	Radius ratios
ν	Kinematic viscosity, [m ² /s]
ρ	Density, [kg/m ³]
Ω	Rotational speed, [rad/s or rpm]
Γ	Aspect ratio
δ	Curvature parameter

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Authors Contribution Statement

Mahmoud Charmiyan: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Supervision, and Project Administration.

Amir Mohammad Hashemi: Software, Validation, Formal Analysis, and Writing – review & editing.

Ali Joodaki: Formal Analysis, Data Curation, Writing – review & editing, and Visualization.

Fethi Aloui: Formal Analysis, Data Curation, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

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