



Thermal–Hydrodynamic Performance of a Rotating LS-2 Parabolic Trough Receiver with Periodic Porous Disks and Syltherm 800: A Numerical Study of Coupled Flow and Rotation Effects

Jamshak Shahul Hameed^{1*}, Sivakumar Krishnamurthy¹, Azeem Hafiz Parayil Ajmal²

¹ Department of Mechanical Engineering, Annamalai University, Annamalai Nagar 608002, India

² Department of Industrial Engineering, King Khalid University, Abha 61421, Saudi Arabia

Corresponding Author Email: jamshak.sh@gmail.com

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<https://doi.org/10.18280/ijht.440423>

ABSTRACT

Received: 9 June 2026

Revised: 12 August 2026

Accepted: 21 August 2026

Available online: 31 August 2026

Keywords:

computational fluid dynamics, parabolic trough solar collector, porous disks, rotating absorber, heat-transfer enhancement

Parabolic trough solar collector (PTSC) of the LS-2 type commonly operate with thermal oils at moderate flow rates, where laminar or weakly transitional flow can produce a thick thermal boundary layer and limit heat transfer from the absorber wall. This study numerically investigates a hybrid enhancement strategy in which the absorber tube is rotated about its axis and discrete porous disks are periodically arranged along its length, using Syltherm 800 as the working fluid. Three-dimensional, steady-state computational fluid dynamics (CFD) simulations are performed for axial velocities of 0.23–0.68 m/s and angular velocities of 5.24–41.89 rad/s. Absorber rotation generates swirl, while the porous disks repeatedly disturb the near-wall flow and enhance radial mixing. Relative to the stationary configuration, rotation substantially increases the average Nusselt number (Nu), with the greatest thermal enhancement occurring at low-to-moderate angular velocities, while further rotation provides diminishing heat-transfer benefits. The results demonstrate the potential of the combined configuration for heat-transfer enhancement in LS-2 receivers. However, pressure drop, hydraulic resistance, and rotational power requirements are not evaluated in the present study and require further investigation for practical performance assessment.

1. INTRODUCTION

Parabolic trough solar collector (PTSC) are among the most mature concentrated-solar-power technologies. A linear parabolic reflector focuses direct radiation onto a cylindrical absorber tube placed along its focal line, and a circulating heat-transfer fluid (HTF) carries the absorbed energy to a power block or storage. The LS-2 collector, with its standardized aperture, focal length, and evacuated receiver, has become a reference geometry for both experiments and simulation [1], which makes it a natural test bed for new enhancement concepts as shown in Figure 1.

A persistent limitation of thermal-oil PTSC is internal heat transfer. To keep pumping power low, the oil is circulated slowly, so the receiver flow is often laminar or only weakly transitional; convective transport is modest and a thick thermal boundary layer forms on the inner wall, acting as the controlling resistance between the heated wall and the bulk fluid. Poor internal transfer also produces steep circumferential and axial wall-temperature gradients, which may increase the potential for thermal-stress development. Improving the internal thermal–hydrodynamic behavior of the absorber is therefore important for enhancing the transfer of absorbed solar energy to the HTF and improving temperature uniformity.

Enhancement techniques are usually grouped as passive (no

external power: roughened surfaces, fins, twisted tapes, wire coils, ribs, porous inserts) or active (external input: pulsation, applied fields, vibration, wall rotation) [1–3]. Porous inserts are attractive in laminar and transitional flow because they enlarge the wetted area, break up the boundary layer, and promote mixing; arranging them as discrete disks rather than a continuous filling gives better control of the flow disturbance and associated pressure penalty [4–6]. Their drawback is the associated flow resistance, which can increase the pumping requirement. Therefore, the placement and resistance of the inserts must be considered together with the resulting thermal enhancement.

Rotating the absorber about its own axis is a complementary, active mechanism. The rotating wall imparts a tangential velocity to the fluid; combined with the axial flow this produces swirl and cross-stream circulation that mix the core with the near-wall region and reduce temperature stratification. Because rotation reorganizes the whole flow field rather than acting locally, it can enhance transfer along the entire receiver even at a low Reynolds number (Re) [7, 8], which is useful for thermal-oil loops where reaching turbulence by raising the flow rate is impractical. The practical implementation of a rotating receiver requires bearings, seals, and a mechanical drive system, and the associated parasitic power consumption and mechanical reliability must be considered when assessing its practical feasibility.

Combining periodic porous disks with wall rotation is the strategy examined here, as shown in Figure 2. The disks provide repeated, local boundary-layer interruption, while rotation provides global swirl. Their interaction is not a simple superposition: rotation modifies the flow approaching each porous disk, while the disk-induced disturbances influence the development of the rotation-induced secondary flow downstream. This coupled interaction affects radial mixing, thermal-boundary-layer redevelopment, and heat transfer, and depends on flow velocity, angular velocity, porous resistance and fluid properties, making three-dimensional CFD appropriate for investigating the combined effects. Syltherm 800, a silicone thermal oil widely used at intermediate temperatures, is adopted as the HTF; its good thermal stability and comparatively low thermal conductivity make it a demanding and realistic fluid for testing heat-transfer enhancement [9, 10].

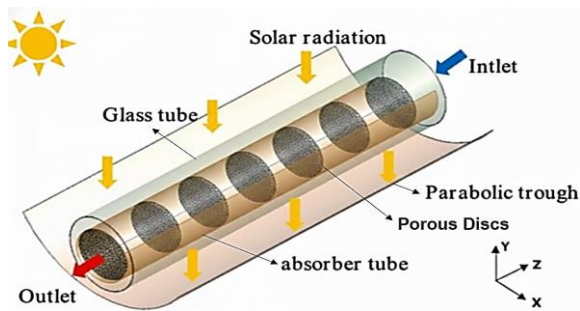


Figure 1. Geometry and working principle of an LS-2 parabolic trough solar collector (PTSC)

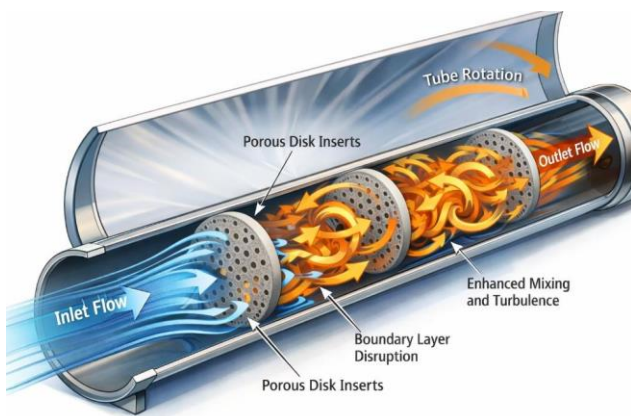


Figure 2. Conceptual illustration of porous-disk inserts and their role in boundary-layer disruption and mixing

Three gaps motivate the study. Most prior work treats a single mechanism—porous inserts or rotation—rather than their combination; few studies examine the LS-2 geometry with a realistic thermal oil while investigating the coupled effects of absorber rotation and periodic porous disks; and the physical interaction between the two enhancement mechanisms remains insufficiently understood. Accordingly, this paper solves the steady, three-dimensional flow and energy equations for a rotating LS-2 absorber fitted with periodic porous disks and reports the coupled response to axial and angular velocity in terms of flow characteristics, temperature distribution, and heat-transfer performance. The study aims to identify the rotational conditions that provide the greatest thermal enhancement and to clarify the associated

flow characteristics, while recognizing that pressure drop, hydraulic resistance, and mechanical power requirements require further investigation.

2. LITERATURE REVIEW

Research on receiver-side enhancement in PTSC falls into four strands — porous media, solid inserts and turbulators, advanced working fluids, and rotation-induced secondary flow — united by a performance-evaluation framework that weighs thermal gain against the pressure penalty.

2.1 Porous media and porous-disc receivers

Porous inserts enlarge the effective surface area, repeatedly disrupt the boundary layer and promote radial mixing, and are most effective in the laminar-to-transitional regime typical of thermal-oil receivers, as shown in Figure 3. Kumar and Reddy [5] established the receiver-scale behavior of porous and perforated-disc inserts and quantified the pumping-cost trade-off, finding that alternately spaced discs outperform fully packed arrangements [6]. Darbari et al. [4] provided the closest geometric precedent, numerically optimizing metal-foam porous disks in an LS-2 receiver and reporting a thermal-efficiency improvement of a few per cent with a modest PEC gain alongside higher pressure drop. Recent studies confirm both promise and cost: internal annular porous structures with synthetic-oil/ Al_2O_3 nanofluid [11], silicon porous discs with paraffin for combined enhancement and storage [12], and porous inserts coupled with nanofluids in a novel LS-2 receiver [13]. Volumetric-absorption metal foam [14, 15] and porous-media receivers in solar towers [16] and receiver-reactors [17] extend the same principles. Diafi et al. [18] studied square porous media with Syltherm 800 at porosities of 0.91 and 0.95, directly comparable with the present 0.95 disks. The recurring conclusion is that porous enhancement must be reported together with its pressure penalty.

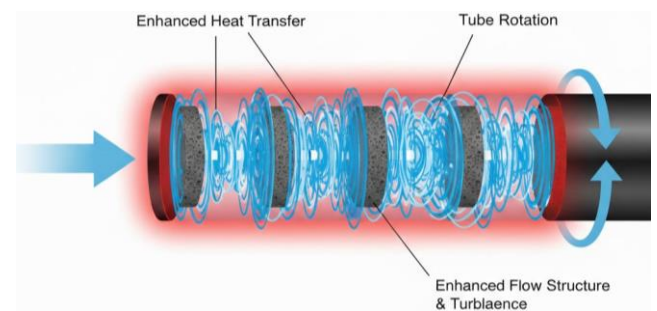


Figure 3. Combined effect of absorber-tube rotation and porous-disk inserts on flow structure and heat-transfer enhancement

2.2 Solid inserts and turbulators

Solid inserts generate swirl or repeated separation without distributed resistance. Centrally placed perforated-plate inserts raise receiver performance with a quantified entropy penalty [19], while wavy-tape inserts were used to manage the highly non-uniform circumferential flux [20]. Internally finned absorbers have been analyzed for thermal enhancement [2] and through multi-criteria optimization balancing thermal and hydraulic effects [3]. Twisted tapes remain among the most

studied turbulators, with large Nu and friction-factor changes reported together with energy, exergy and environmental metrics [21], and recent work combines tapes or fins with nanofluids and dimpled or finned tubes [22–24]. Conical and conical-dimpled receivers [25, 26] and inner tubes with wing-like fringes [27] illustrate the breadth of passive options. A consistent finding is that inserts giving the highest Nu also incur the steepest friction penalties, so the PEC — not the Nu alone — governs practical value.

2.3 Advanced working fluids

Because Syltherm 800 combines good thermal stability with comparatively low thermal conductivity, much effort has gone into improving the fluid. Synthetic-oil/ Al_2O_3 nanofluid receivers have been optimized thermodynamically [9], and hybrid and ternary nanofluids report incremental efficiency gains that depend strongly on concentration and inlet temperature [28, 29]. Fluid-side and geometry-side enhancement are complementary, and nanofluid stability and cost remain practical barriers — motivating robust mechanical techniques such as the present one.

2.4 Rotation and rotation-induced secondary flow

Rotation introduces Coriolis and centrifugal effects that reorganize the velocity and temperature fields and generate secondary swirling motion, long exploited in turbomachinery cooling and increasingly studied for solar receivers. Norouzi et al. [7] experimentally demonstrated that rotating the absorber tube improves heat transfer and yields more uniform wall temperatures—spinning tube fins with ternary nanofluids [8], and rotating inserts that raise thermal efficiency relative to stationary arrangements [30]. These works establish that rotation can enhance transfer even at a low Re , but also note rising friction and mechanical complexity at high rotation rates, and none combines rotation with periodic porous disks in an LS-2 receiver using Syltherm 800.

2.5 Performance evaluation and research gap

The enhancement literature is unanimous that heat-transfer gains must be reported alongside their pressure penalty, typically through $PEC = (Nu/Nu_0)/(ff_0)^{(1/3)}$ [31]. Synthesising the four strands, porous inserts and rotation each enhance LS-2 receiver heat transfer, advanced fluids add incremental gains, and the PEC frames their net value; yet their combined use—periodic porous disks with wall rotation, in the LS-2 geometry, with Syltherm 800, evaluated on both thermal and hydrodynamic terms—has not been reported in a single, consistent study. Closing that gap is the contribution attempted here.

3. PROBLEM DESCRIPTION AND METHODOLOGY

3.1 Physical model

The computational domain is the internal fluid region of an LS-2 absorber tube of inner diameter $D = 60$ mm ($R = 30$ mm) and length $L = 7.8$ m. Porous disks of thickness $0.25 R$ are placed periodically with spacing $a = 3 R$ and rotate rigidly with the tube about its longitudinal axis (Figures 4–6). External optical and radiative processes are represented by a prescribed

heat flux on the inner wall, so only the fluid region is solved. The flow is steady, incompressible, single-phase and Newtonian, with temperature-dependent properties of Syltherm 800.

At the inlet, a uniform axial velocity (0.23, 0.46, or 0.68 m/s) and a uniform temperature are imposed. At the outlet, a pressure-outlet condition with zero-gauge pressure is used. The inner wall is no-slip and rotates at the prescribed angular velocity (5.24, 10.47, 20.94, or 41.89 rad/s), with a heat flux representing the concentrated solar irradiation. The porous disks are modelled as isotropic porous media using the Darcy–Forchheimer resistance and rotate with the wall. A porosity of approximately 0.95, a permeability of $1.0 \times 10^{-8} \text{ m}^2$, and a Forchheimer coefficient of $1.0 \times 10^5 \text{ m}^{-1}$ are adopted. The corresponding viscous resistance is $1.0 \times 10^8 \text{ m}^{-2}$. The adopted assumptions are: steady flow and heat transfer; in-tube radiation neglected; negligible axial conduction in the fluid; buoyancy neglected under forced-convection dominance; and rigid rotation of the tube.

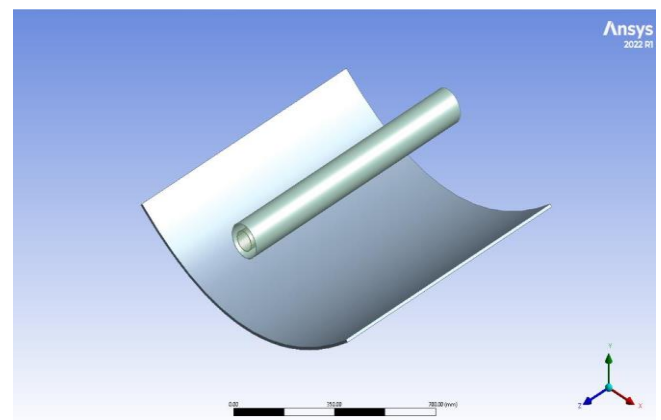


Figure 4. LS-2 receiver assembly: parabolic collector, glass cover and receiver tube

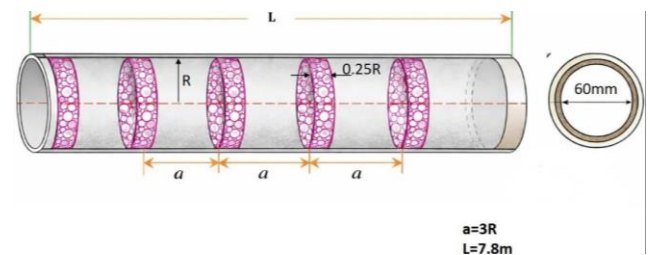


Figure 5. Schematic of the rotating absorber with periodic porous disks ($D = 60$ mm, $L = 7.8$ m, thickness $0.25 R$, spacing $a = 3 R$)

Steady flow and heat transfer are assumed because the inlet velocity, wall heat flux, and rotational speed are kept constant. In-tube radiation is neglected because the solar input is already represented by the prescribed wall heat flux. Axial conduction is neglected because convection dominates at the investigated flow velocities. Buoyancy is also neglected because forced convection is dominant, although its effect may be more noticeable at the lowest velocity (0.23 m/s). The selected axial and angular velocities were chosen as a systematic range to investigate the effects of increasing HTF flow and absorber rotation, with reference to previous studies on LS-2 and rotating parabolic-trough receivers [28, 30]. The absorber tube and porous disks are assumed to rotate together as a rigid assembly.

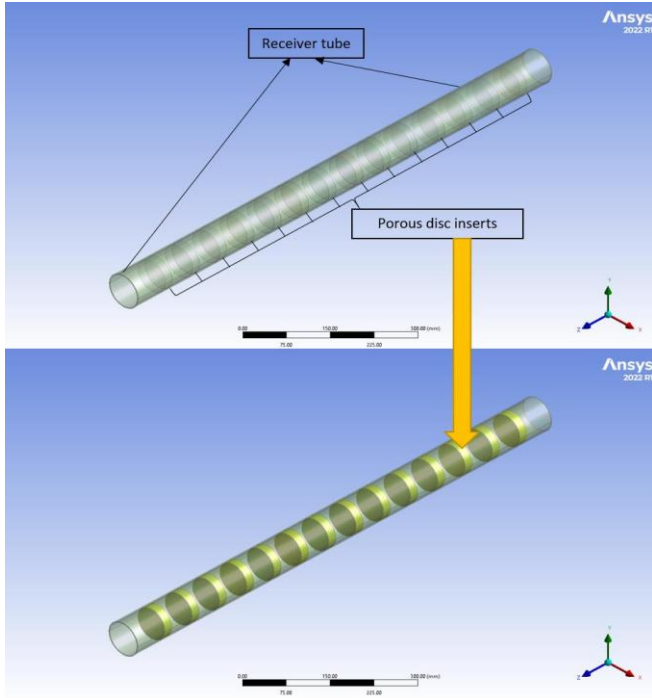


Figure 6. Computational geometry of the receiver tube and the periodic porous-disk inserts

3.2 Governing equations

Conservation of mass, momentum (in a rotating frame with angular velocity Ω), and energy are solved:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} - 2\rho(\Omega \times \mathbf{u}) - \rho\Omega \times (\Omega \times \mathbf{r}) + S_{porous} \quad (2)$$

$$\rho c_p(\mathbf{u} \cdot \nabla T) = \nabla \cdot (k \nabla T) \quad (3)$$

where, $2\rho(\Omega \times \mathbf{u})$ is the Coriolis force and $\rho\Omega \times (\Omega \times \mathbf{r})$ the centrifugal force. The porous resistance is the Darcy–Forchheimer source:

$$S_{porous} = -(\mu/K \cdot \mathbf{u} + C_F \cdot |\mathbf{u}|^2 \rho |\mathbf{u}|) \quad (4)$$

with permeability K and inertial-resistance coefficient C_F . Within the disks, an effective-conductivity balance is used:

$$(\rho c_p)_{eff}(\mathbf{u} \cdot \nabla T) = \nabla \cdot (k_{eff} \nabla T), k_{eff} = \varepsilon k_f + (1 - \varepsilon)k_s \quad (5)$$

where, ε is the porosity and k_f, k_s are the fluid and solid-matrix conductivities; local thermal equilibrium is assumed. Heat-transfer metrics follow from the wall heat flux and the average wall and bulk temperatures:

$$h = q''/(T_w - T_b), Nu = hD/k \quad (6)$$

$$Nu_{enhancement} (\%) = (Nu - Nu_{stat})/Nu_{stat} \times 100\% \quad (7)$$

3.3 Numerical procedure

The equations are discretized by the finite-volume method

in ANSYS Fluent with a pressure-based solver and SIMPLE pressure–velocity coupling. Pressure uses a second-order scheme; momentum and energy use second-order upwind discretization. The porous disks use the built-in porous-media model with the specified permeability and inertial resistance, and rotation is treated in a rotating reference frame. The computational mesh contains approximately 2.5 million cells, with local refinement near the absorber wall and around the porous disks. Ten inflation layers are applied near the wall with a first-layer thickness of approximately 0.05 mm and a growth rate of 1.2, giving a near-wall y^+ value that remains within an acceptable range for the turbulence model employed. Convergence is judged from scaled residuals (10^{-6} for continuity and momentum, 10^{-8} for energy) together with monitored outlet temperature and pressure drop.

4. GRID INDEPENDENCE AND VALIDATION

4.1 Grid-independence study

A structured hexahedral mesh with near-wall inflation layers and local refinement within and around the porous disks was used, following the meshing practice of Darbari et al. [4]. Three densities (coarse, medium, fine) were tested for a representative case. The coarse mesh differed from the medium by more than 5% in average outlet Nu , whereas the medium and fine meshes agreed to within 1.5% in both Nu and pressure drop; the medium mesh was therefore adopted.

4.2 Validation

A non-rotating, porous-disk baseline was run under conditions comparable with Darbari et al. [4], using temperature-dependent Syltherm 800 properties and a wall heat flux matched to their average solar flux. The rotational implementation was checked against canonical rotating-pipe behavior to confirm that the secondary-flow and boundary-layer modifications follow the expected trends. However, direct experimental or correlation-based validation of the coupled rotating porous-disk configuration was not possible because suitable published data are unavailable. Therefore, the rotating results should be interpreted within the scope of the present numerical model.

5. RESULTS AND DISCUSSION

Results are reported for three axial velocities and four angular velocities, with porosity $\varepsilon = 0.95$ and all other parameters held constant.

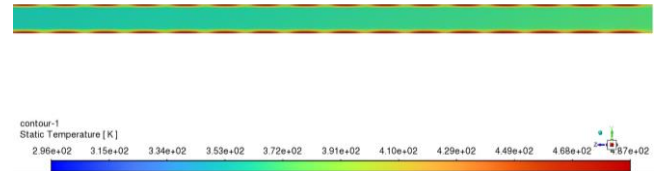


Figure 7. Static-temperature field along the absorber showing periodic boundary-layer disruption ($v = 0.23$ m/s, $\Omega = 5.24$ rad/s)

The contour and vector fields confirm the intended mechanism as shown in Figure 7. The porous disks repeatedly

interrupt the near-wall flow, while the rotating wall imparts a circumferential motion strongest near the wall and decaying toward the center. The combination prevents a stable thermal boundary layer from forming and drives radial exchange between the wall and the core, giving an increasingly uniform cross-sectional temperature toward the outlet.

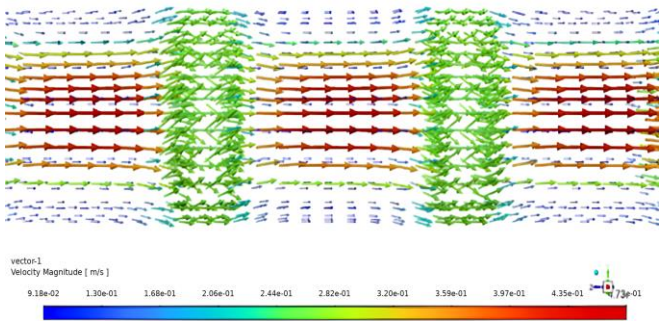


Figure 8. Sectional velocity-vector field demonstrating boundary-layer interruption ($v = 0.23 \text{ m/s}$, $\Omega = 5.24 \text{ rad/s}$)

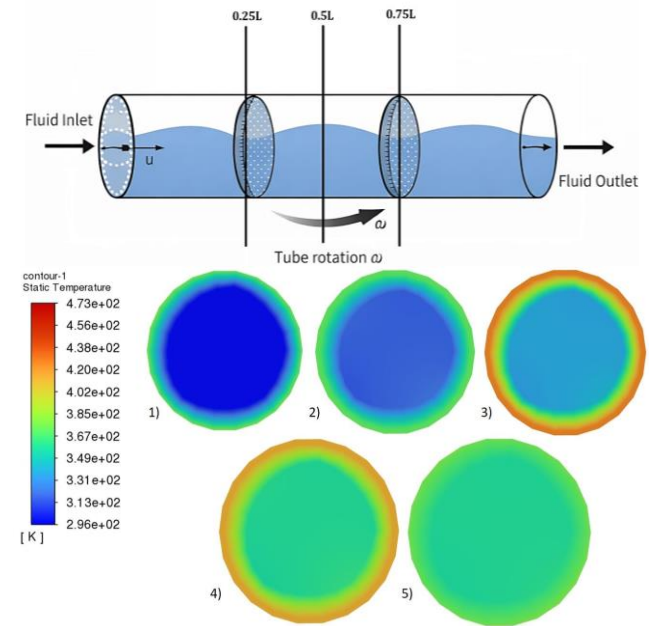


Figure 9. Cross-sectional temperature at inlet, 0.25 L, 0.5 L, 0.75 L and outlet ($v = 0.23 \text{ m/s}$, $\Omega = 20.94 \text{ rad/s}$)

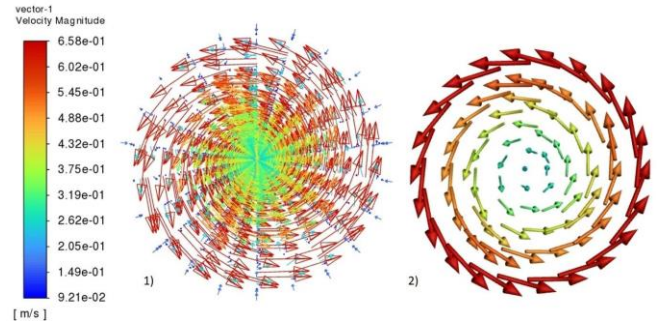


Figure 10. Cross-sectional velocity vectors showing rotation-induced swirl ($v = 0.23 \text{ m/s}$, $\Omega = 20.94 \text{ rad/s}$)

The contour and vector fields show the effect of absorber rotation on the flow and temperature distribution. The rotating wall generates circumferential motion, while the resulting

swirl promotes fluid mixing between the wall and core as shown in Figure 8. This radial mixing reduces temperature differences across the tube and produces a more uniform cross-sectional temperature toward the outlet, supporting the observed heat-transfer enhancement as shown in Figure 9.

The velocity field shows a predominantly axial flow between the porous disks, while strong flow disturbance and circumferential motion are observed around the disks, as shown in Figures 10 and 11. The repeated disks interrupt the developing flow and redistribute the fluid near the wall, producing enhanced mixing downstream of each disk. This repeated flow disturbance helps explain the improved heat transfer observed in the receiver.

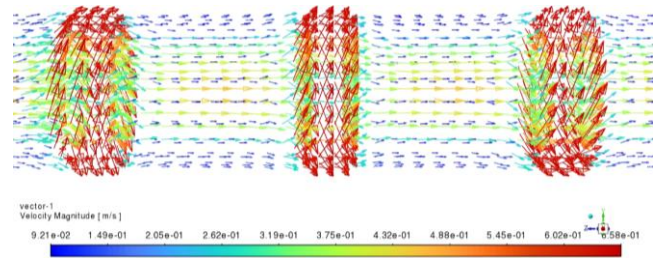


Figure 11. Axial velocity vectors showing flow disturbance produced by the porous-disk inserts

5.1 Effect of axial velocity

Over the range studied, the average Nu is nearly flat with axial velocity (Table 1), attributed to rotation- and insert-driven mixing dominating the transport once established. The implication-high transfer without large mass flow, and hence lower pumping demand—is attractive if confirmed.

Table 1. Average Nusselt number (Nu) versus axial velocity

Velocity (m/s)	Wall Temperature (K)	Outlet Temperature (K)	Average Nu
0.23	424	363.15	290.50
0.46	405	330.61	292.35
0.68	399	319.97	292.00

5.2 Effect of rotational speed

The average Nu peaks at low-to-moderate rotation (5.24–10.47 rad/s) (Figure 12) and eases slightly as Ω rises further as indicated in Table 2. The mechanism of the slight reduction at high Ω should be re-examined so that it is consistent with the definition of h in Eq. (6).

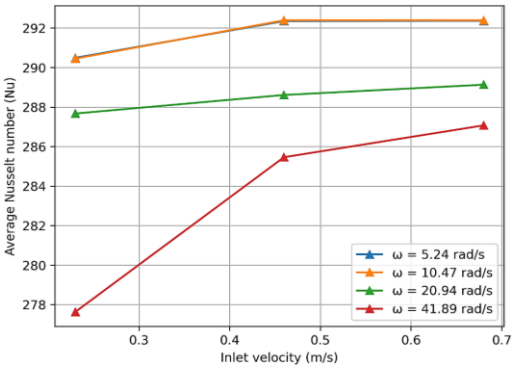


Figure 12. Effect of inlet velocity on average Nusselt number (Nu) at different rotational speeds

Table 2. Average Nusselt number (Nu) versus angular velocity ($v = 0.46$ m/s)

Angular Velocity (rad/s)	Average Nu	Enhancement vs. Stationary (%)
0 (stationary)	91.00	—
5.24	292.35	221.30
10.47	292.39	221.40
20.94	288.61	217.10
41.89	285.46	213.70

5.3 Combined thermal–hydrodynamic performance

Across all cases, the average Nu remains within a narrow range, with the highest values at low-to-moderate rotation for all velocities as indicated in Table 3. The wall temperature decreases, and the outlet temperature becomes more uniform with increasing velocity and rotation, which may reduce temperature non-uniformity and potential thermal-stress risks. At low-to-moderate rotation, swirl superimposed on the axial flow thins the thermal boundary layer and periodically disrupts its redevelopment downstream of each porous disk, enhancing radial heat transport from the wall. At higher rotation, this benefit diminishes: the flow becomes increasingly tangential, so additional swirl contributes less to radial mixing, while stronger circumferential shear raises wall friction and dissipates more momentum viscously rather than disrupting the boundary layer further. The result is a rotation-dominated flow that is less mixing-effective, producing the observed reduction in average Nu at higher rotational speed (Figure 13).

Table 3. Combined influence of axial and angular velocity ($\varepsilon = 0.95$)

v (m/s)	Ω (rad/s)	Wall Temperature (K)	Outlet Temperature (K)	Average Nu
0.23	5.24	424.00	363.15	290.49
0.23	10.47	424.00	363.13	290.45
0.23	20.94	424.00	361.56	287.67
0.23	41.89	425.00	357.40	277.63
0.46	5.24	405.00	330.61	292.35
0.46	10.47	405.00	330.63	292.39
0.46	20.94	406.00	330.32	288.61
0.46	41.89	406.00	328.55	285.46
0.68	5.24	399.00	319.97	292.36
0.68	10.47	399.00	319.99	292.39
0.68	20.94	400.00	319.98	289.13
0.68	41.89	400.00	318.84	287.07

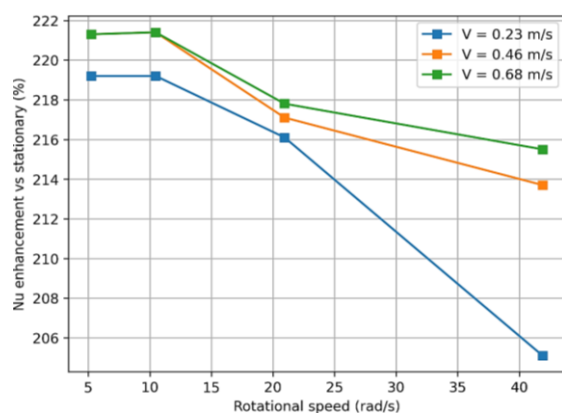


Figure 13. Enhancement of average Nusselt number (Nu) relative to the stationary pipe versus rotational speed

5.4 Discussion and engineering implications

Periodic porous disks and wall rotation act at different scales—local boundary-layer interruption and global swirl—and jointly enhance near-wall mixing. Their effects are complementary at low-to-moderate rotation, where disk-induced disturbances are redistributed circumferentially by swirl. Beyond this range, circumferential shear dominates the flow structure, suppressing the radial fluctuations responsible for the disks' mixing benefit and increasing swirl-related pressure losses, so higher rotation yields diminishing thermal returns. The associated hydraulic and mechanical penalties were not quantified here and require further investigation. This trend is consistent with rotating-absorber studies of PTSC [28, 30].

5.5 Summary of findings

The combination of wall rotation and porous disks raises the average Nu well above the stationary case, with the maximum at low-to-moderate angular velocity; axial velocity has a comparatively weak effect within the range studied; and the configuration delivers lower wall temperatures and a more uniform outlet field.

6. CONCLUSIONS

A three-dimensional CFD study examined a rotating LS-2 parabolic-trough receiver fitted with periodic porous disks and operating with Syltherm 800. Wall rotation combined with the disks enhances convective heat transfer relative to the stationary configuration, with the largest average Nu obtained at low-to-moderate angular velocities (5.24–10.47 rad/s) and only a weak dependence on axial velocity once rotation-induced mixing is established. The combined action of the porous disks and rotation enhances radial mixing, lowers peak wall temperature, and produces a more uniform outlet temperature. These thermal characteristics may help reduce temperature non-uniformity and potential thermal-stress risks; however, thermal stress, material degradation, and long-term receiver durability are not directly evaluated. The present study also lacks experimental validation and does not quantify the rotational power requirement or its effect on the net thermal benefit. Future work should therefore include experimental validation, optimization of the porous geometry under rotation, quantification of rotational power consumption relative to the thermal gain, and assessment of long-term operational stability and overall system efficiency.

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NOMENCLATURE

a	disk spacing, m
C_F	inertial-resistance coefficient, dimensionless
c_p	specific heat, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
D	absorber inner diameter, m
f	Darcy friction factor, dimensionless
f_0	friction factor for the reference configuration
h	convective heat-transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
K	permeability, m^2
k	thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$

L	absorber length, m
Nu	Nusselt number, dimensionless
Nu_0	Nusselt number for the reference configuration
PEC	performance evaluation criterion, dimensionless
Pr	Prandtl number, dimensionless
p	static pressure, Pa
q''	wall heat flux, $\text{W}\cdot\text{m}^{-2}$
R	absorber inner radius, m
Re	Reynolds number, dimensionless
T	temperature, K
Ta	Taylor number, dimensionless
u	velocity vector, $\text{m}\cdot\text{s}^{-1}$

Greek symbols

ε	porosity, dimensionless
μ	dynamic viscosity, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$
ρ	density, $\text{kg}\cdot\text{m}^{-3}$
Ω	angular velocity, $\text{rad}\cdot\text{s}^{-1}$

Subscripts

b	bulk
eff	effective
f	fluid
s	solid matrix
$stat$	stationary