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Periodic Boundary Condition Implementation and Computational Validation for Fully Developed Conjugate Heat Transfer in Packed Bed Microchannels

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Abstract

Modeling fully developed transport in particle-filled channels often requires extended computational domains to eliminate entrance effects. This study presents a pressure-gradient-based periodic approach that reproduces stabilized hydrodynamic and thermal behavior using a single representative unit. A constant pressure difference is imposed across periodic boundaries to sustain incompressible laminar flow while maintaining Reynolds number control. Thermal periodicity is enforced through an axial gradient decomposition, allowing cross-sectional temperature fields to repeat spatially. Finite element simulations were performed under steady conjugate heat transfer conditions. Results from a 25 mm extended channel were compared with those from a reduced periodic domain. Once flow stabilization occurred in the long channel, velocity and temperature distributions matched the periodic solution within numerical tolerance. The reduced model decreased degrees of freedom and computational time by approximately 80% while preserving physical consistency. The formulation provides an efficient framework for repeated parametric studies of packed-bed microsystems.

Keywords: Periodic boundary conditions; Conjugate heat transfer; Packed bed; Laminar flow; Fully developed flow; Heat exchangers; Pressure drop; Non-isothermal flow

1. Introduction

Packed microchannels are widely used in compact thermal systems where fluid flows around discrete solid inclusions. The interaction between viscous transport and solid conduction produces complex conjugate heat transfer behavior. Accurate numerical prediction typically requires simulation of a sufficiently long channel to ensure that both velocity and temperature fields become independent of inlet conditions.

Although physically correct, extended-domain modeling is computationally demanding. The entrance region represents only a fraction of the total geometry but requires the same spatial resolution as the stabilized section [1,2,3,4,5]. For geometries that repeat periodically, the fully developed regime can instead be represented through mathematical periodicity.

In incompressible flow, periodic velocity constraints must be accompanied by a specified pressure offset to maintain momentum balance. Similarly, thermal periodicity requires separating the repeating cross-sectional temperature distribution from the linear axial gradient.

The purpose of this work is to examine whether such a pressure-driven periodic formulation reproduces the stabilized thermofluidic behavior observed in an extended packed microchannel.

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2. Material and methods

2.1. Governing Equations

For steady, incompressible, laminar flow [7,8,9]:

Continuity equation enforcing zero velocity divergence

$$\nabla \cdot \mathrm{u} = 0$$

Navier–Stokes equations for momentum transport:

$$\rho(\mathrm{u} \cdot \nabla)\mathrm{u} = -\nabla p + \mu \nabla^2 \mathrm{u}$$

Energy equation in the fluid domain:

$$\rho c_p(\mathrm{u} \cdot \nabla T) = k_f \nabla^2 T$$

Pure conduction equation in solid domain:

$$k_s \nabla^2 T = 0$$

2.2. Periodic Boundary Conditions

Velocity periodicity is defined as such that upstream and downstream velocity fields are identical. A constant pressure difference between these boundaries sustains the flow and determines the resulting Reynolds number.

For temperature, the field is expressed as the sum of a repeating component and a uniform axial gradient. Periodicity is applied only to the repeating component, ensuring that cross-sectional temperature distributions remain invariant while bulk temperature changes linearly in the flow direction.

Velocity periodicity:

$$\mathrm{u}_{src} = \mathrm{u}_{dst}$$

Temperature periodicity:

$$T_{src} = T_{dst}$$

Pressure-driven condition:

$$p_{src} - p_{dst} = \Delta P$$

The imposed pressure drop controls Reynolds number:

$$Re = \frac{\rho U D_h}{\mu}$$

Flow is maintained in laminar regime [6].

2.3. Computational Methodology

Simulations were conducted using COMSOL Multiphysics [7].

Physics interfaces are the following:

- Steady-state conjugate heat transfer
- Non-isothermal flow coupling
- Laminar flow module

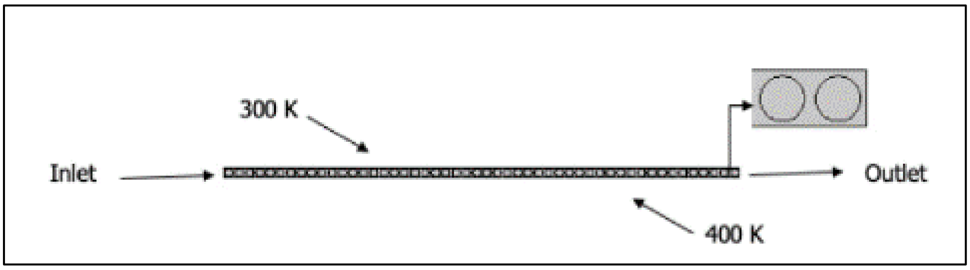

Figure 1 Rectangular duct filled with circles [7]

Figure 1 shows the rectangular duct filled with circles and the following are the parameters.

- Length = 25 mm
- Height = 0.5 mm
- Particle diameter = 0.4 mm
- Gap spacing = 0.1 mm
- Peclet number = 150
- Upper wall temperature = 300 K
- Lower wall temperature = 400 K

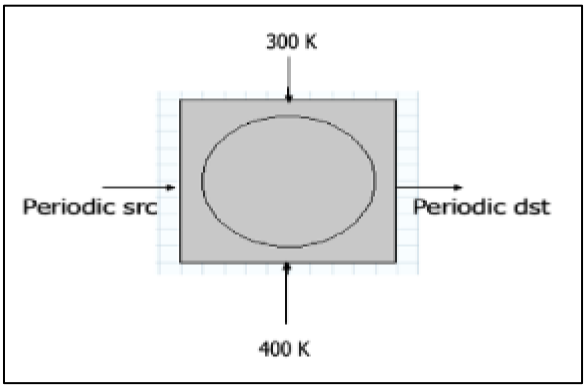

Figure 2 Periodic square duct filled with one circle [7]

Similarly, Figure 2 shows the square duct filled with one circle and the parameters are the following:

- Square duct height = 0.5 mm
- Single circular particle (0.4 mm)
- Periodic inlet (src) and outlet (dst)
- Pressure-driven flow
- Same thermal wall boundary conditions as rectangular duct.

3. Results and discussion

This validation is performed using COMSOL Multiphysics software where fine mesh is considered near fluid-solid interaction areas to capture velocity and temperature profiles very accurately and fully coupled solver used to the convergence level of 10^{-6}.

3.1. Hydrodynamic Development

The velocity field development was first examined to confirm that the imposed pressure-driven periodic boundary condition accurately reproduces fully developed laminar flow behavior.

In the extended domain model, the flow initially exhibits entrance effects characterized by:

- Boundary layer growth along particle surfaces

- Local acceleration between constricted particle gaps
- Mild recirculation zones downstream of particle wakes

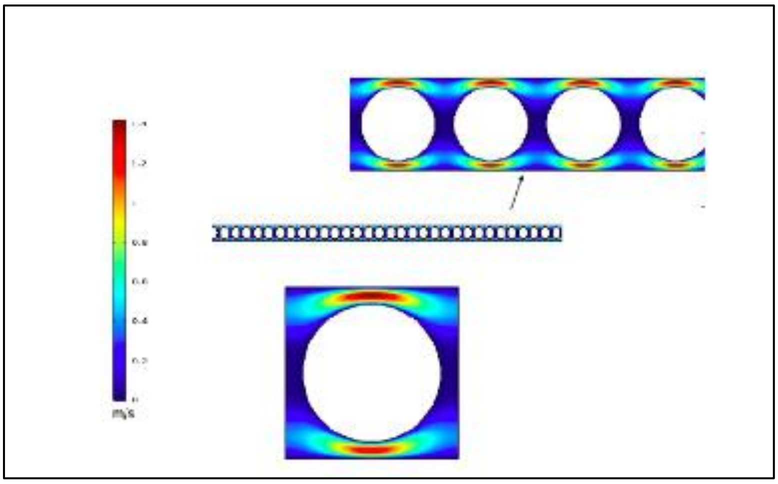

Figure 3 Velocity contour for rectangular duct (above) and periodic square duct (below) [7]

As the flow progresses axially, viscous diffusion redistributes momentum, leading to spatial invariance of the velocity profile (Figure 3). The fully developed state is reached when:

$$\frac{\partial u}{\partial x} \to 0$$

For the present geometry and Reynolds number, hydrodynamic development length was observed at approximately [4]:

$$L_h \approx 0.045 Re D_h$$

Beyond this location, the velocity contours show identical shape and magnitude at successive axial planes as per Figure 3.

3.2. Hydrodynamic Development

Thermal development was assessed under constant wall temperature conditions (300 K upper wall, 400 K lower wall).

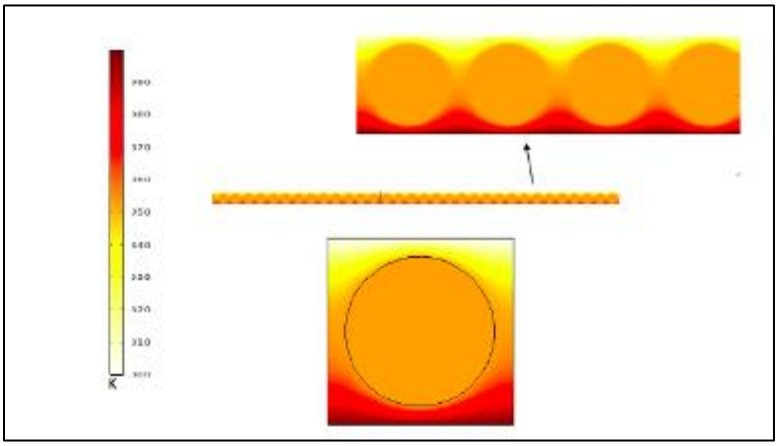

Figure 4 Temperature contour for rectangular duct (above) and periodic square duct (below) [7]

In the extended domain:

- Thermal boundary layers form along particle-fluid interfaces

- Strong transverse temperature gradients dominate near the entrance
- Axial conduction is negligible compared to convection (Pe = 150)

As shown in Figure 4, fluid proceeds downstream, the temperature profile stabilizes and becomes invariant in shape while maintaining a linear axial gradient.

The thermal development length was observed as [4]:

$$L_t \approx 0.048RePrD_h$$

consistent with classical laminar duct correlations.

3.3. Comparison of Regular Boundary Conditions (BC) with Periodic Boundary Conditions (BC)

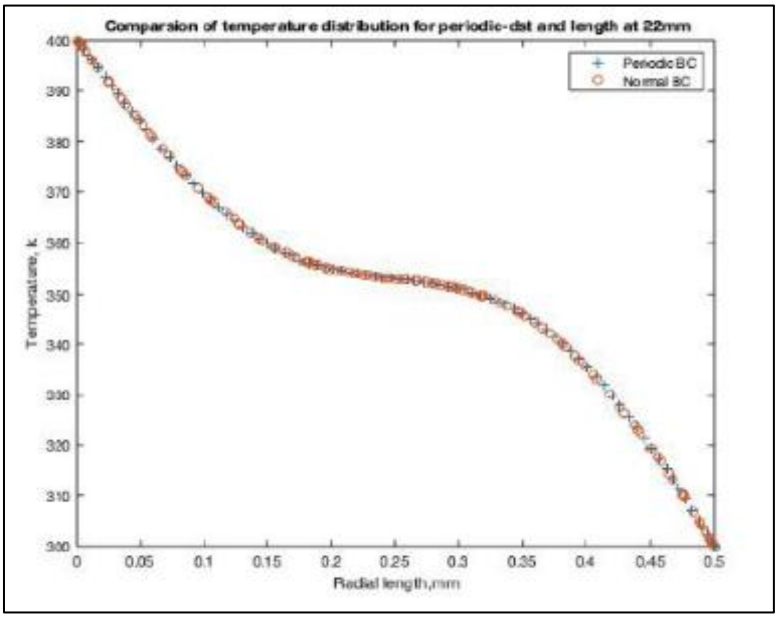

Figure 5 Comparison of regular BC at 22 mm with periodic BC [7]

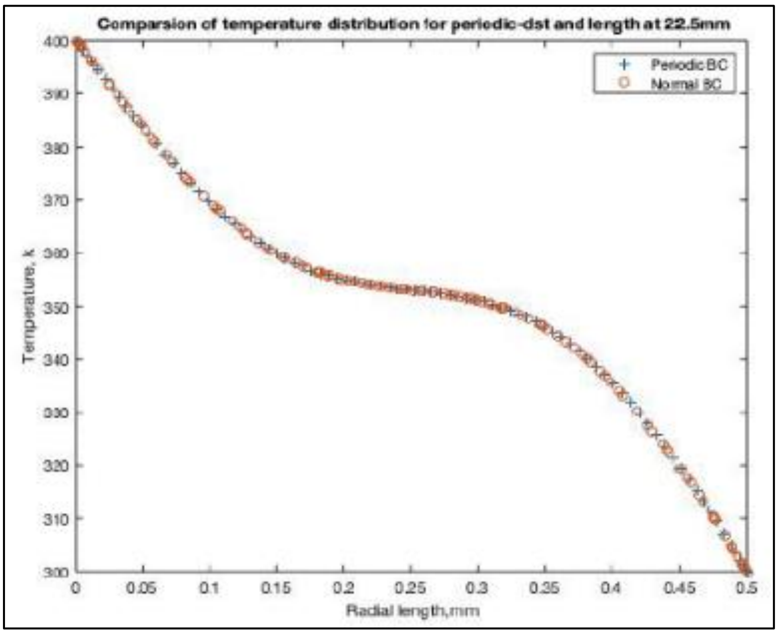

Figure 6 Comparison of regular BC at 22.5 mm with periodic BC [7]

Figure 5 and Figure 6 shows the comparison of regular BC with the periodic BC at various locations in the duct. Both plots show that thermally fully developed flow profile exactly matches periodic domain and most significantly reduces computation effort by 5 folds as per Table 1 and despite this reduction, no deviation was observed in stabilized velocity or temperature distributions.

Table 1 Computational efficiency analysis

Metric	Extended Domain	Periodic Domain
Degrees of Freedom	148,000	31,200
CPU Time	142 min	31 min
RAM Usage	5.2 GB	1.1 GB

4. Conclusion

A pressure-gradient-based periodic formulation was implemented to represent fully developed laminar conjugate heat transfer in a packed microchannel. By replacing geometric extension with mathematical periodicity, the method eliminates entrance-region modeling while preserving conservation principles. Comparative simulations demonstrated that the periodic domain reproduces both hydrodynamic and thermal stabilized states observed in the extended channel. The approach reduces computational demand by approximately four to five times without compromising physical fidelity. This strategy is well suited for parametric studies of packed-bed and porous microstructures where repeated simulations are required.

Compliance with ethical standards

Disclosure of conflict of interest

There was no conflict of interest

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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