

Thermal-hydraulic Behaviour of Corrugated Pipe Configurations

Aryan Tyagi¹, Gaurav Kumar^{2,*}, Raj Kumar Singh³

Abstract

Heat exchangers have a wide range of applications and can be found in a variety of different industries, including chemical reactors, nuclear power plants, and solar energy generation. It is required to do thermal optimization on heat exchangers in order to decrease the size, cost, and energy requirements of the heat exchangers while simultaneously improving their capacity to transmit heat. In these types of businesses, heat exchangers frequently make use of corrugated pipes as piping material. They are put to use in the process of transferring heat across fluids that are maintained at varying temperatures. The flow of corrugated pipe was investigated by using different corrugated ring diameters, maintaining a corrugated ring angle of 360°, and keeping the spacing between the corrugated rings at 7.5 mm. At a Reynolds number of 5000, the focus of the study was on determining how the diameter of the ring effects the thermo-hydraulic flow of water. Utilizing various forms of numerical simulation, this study determined the thermo-hydraulic flow behaviour and the enhancement of heat transfer of fluid that was moving through a corrugated pipe while a constant heat flux was present. An enhancement in heat transfer coefficient can be confirmed because increase in turbulent kinetic energy was seen. There has been discussion over the impact that the diameter of the corrugated ring has on the behaviour of variables such as velocity, pressure, radial velocity, axial velocity, temperature distribution, and turbulent kinetic energy (TKE).

Keywords: Heat transfer, corrugated pipe, CFD, heat exchanger, thermal enhancement

INTRODUCTION

Heat exchangers are used in a number of different industries, such as solar energy, nuclear power production and chemical reactors [1–5]. Thermal optimization of heat exchangers is necessary to reduce the size, cost, and energy requirements, while at the same time enhancing their heat transfer capabilities. The use of corrugated pipes in heat exchangers is quite common in these industries. They

are used to transfer heat between fluids kept at different temperatures [6–9]. Thermal enhancement of heat exchangers can be done in two ways, namely, active and passive techniques. Active methods require external power sources to produce surface vibration or to drive a mechanical device. Passive methods, as the name suggests, do not require any external power to enhance the performance of the heat exchanger. Passive techniques use extended or rough surfaces, or fluid additives to improve the heat transfer between the fluids. The use of corrugated pipes comes under the passive type of thermal enhancement. Corrugated pipes have been used in many applications to improve the performance of heat exchangers [10–12].

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Received Date: August 27, 2022

Accepted Date: November 24, 2022

Published Date: November 30, 2022

Citation: Aryan Tyagi, Gaurav Kumar, Raj Kumar Singh. Thermal-hydraulic Behavior of Corrugated Pipe Configurations. Journal of Polymer & Composites. 2022; 10(Special Issue 1): S108–S114.

Many numerical and experimental studies on corrugated pipes show their capabilities of enhancing heat transfer. Some Researchers performed experiments using active and passive techniques to improve heat exchanger performance. In their study, corrugated copper pipes with diameter 10 mm and length 3200 mm were used. They studied the thermal performance for different experimental conditions and the drop in pressure for different flow rates. They concluded that rotation of the tubes resulted in a greater pressure drop across the pipes [13]. Some have performed studies that showed a reduction in energy consumption and cost, while improving performance ratings and equipment life. They examined the effects of corrugated rib roughened pipes on frictional losses and heat transfer. The Reynolds number in their study ranged between 7500 and 50,000. The study showed a direct correlation between the number of gaps in the pipe and the Reynolds number of the flow. Increasing the number of gaps with increasing Reynolds number resulted in the increase of friction loss and heat transfer. They also observed an increase in Nusselt number, and the friction factor [14].

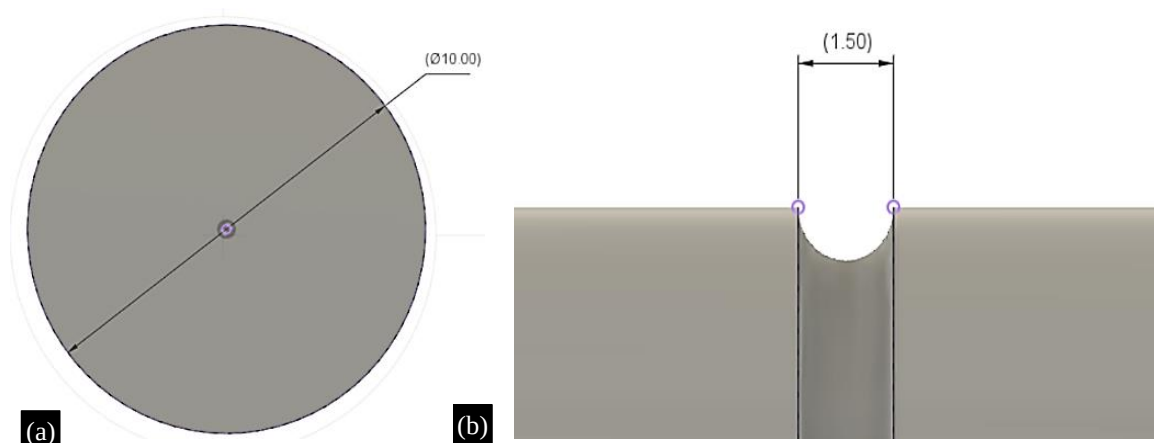
Numerical and experimental studies showed the corrugation angles and their effect on thermal performance of wavy heat exchangers. Their studies were performed in two-dimensional flows. They achieved a performance factor of 1.8 at a corrugation angle of 100° , and a Reynolds number of 1000. They observed a change from transition flow to turbulent flow in the channel, with an increase in the corrugation angle [15]. A study developed a three-dimensional model on ANSYS, studying the heat transfer in helically corrugated pipes. Their simulations resulted in an improvement in heat transfer performance as well as Nusselt number. The rotational flow showed little effect on the Nusselt number and heat transfer.

In this study, a three-dimensional Finite Volume Method (FVM) model was developed on ANSYS Fluent. Corrugated pipe flows were studied, with varying corrugated ring diameters (1.5, 2.5, and 3.5 mm), with corrugated ring angle of 360° and the distance between the corrugated rings being constant at 7.5 mm. The study was focused on how the ring diameter influences the thermo-hydraulic flow of water at the Reynolds number of 5000.

In the results, the effect of the corrugated ring diameter on the behaviour of velocity, pressure, radial velocity, axial velocity, temperature distribution, and turbulent kinetic energy (TKE) has been discussed. The results of these simulations can be used for further study and design for the enhancement of heat transfer corrugated pipe flows.

MODEL DESCRIPTION

The three-dimensional models for the corrugated pipes with different corrugated ring diameters were created in Fusion 360. The CAD models with the parameters are shown in Figure 1. The pipe length and diameter were 1000 and 10 mm, respectively.



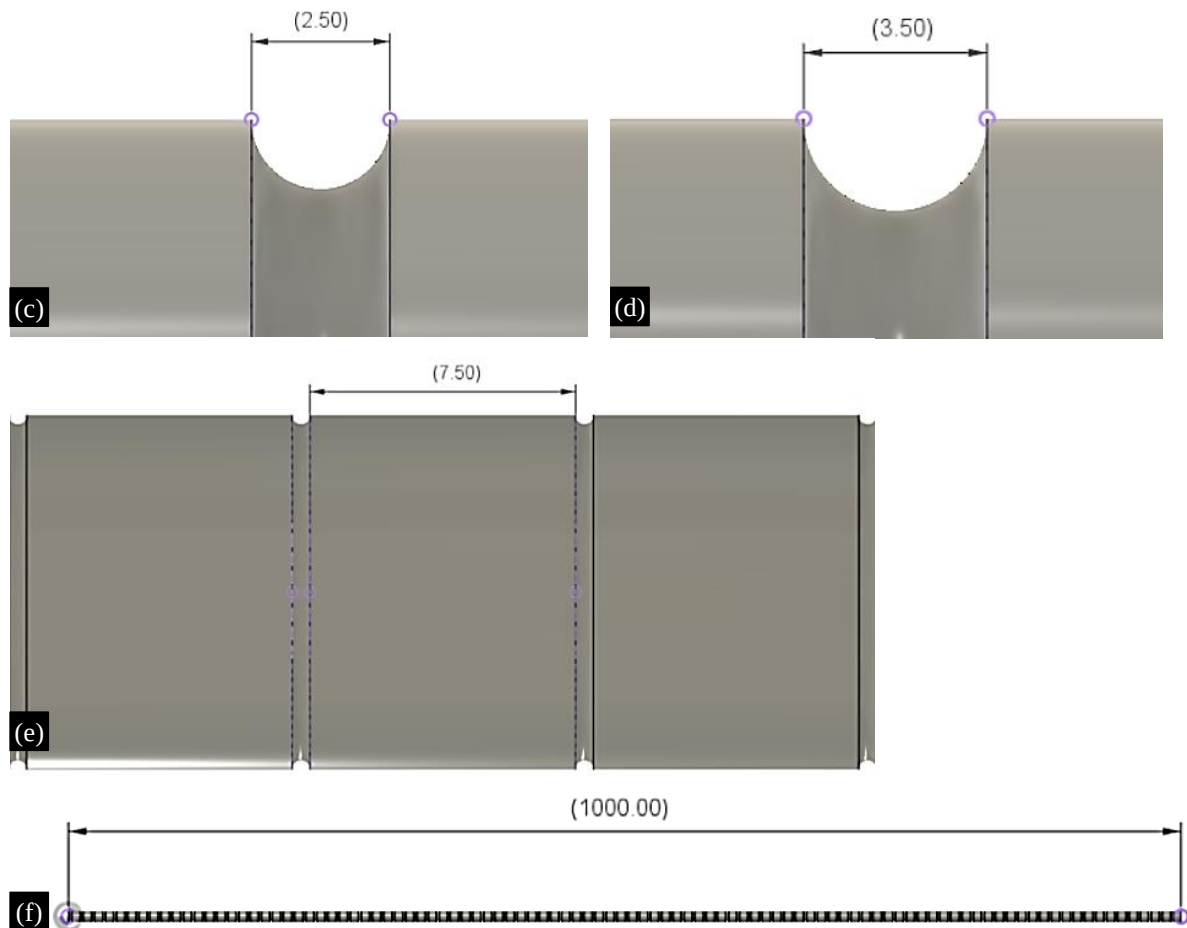


Figure 1. Geometrical Parameters of Corrugated Pipes. (a) Pipe diameter = 10 mm; (b) Corrugated Ring Diameter = 1.5 mm; (c) Corrugated Ring Diameter = 2.5 mm; (d) Corrugated Ring Diameter = 3.5 mm; (e) Gap between each ring is 7.5 mm; (f) Length of the entire pipe is 1000 mm.

There was a total of four geometries for the corrugated pipes used in this study. Each geometry had a corrugated ring angle of 360° , distance between rings is 7.5 mm and the ring diameter ranges from 1.5 to 3.5 mm, with increments of 1 mm. The last geometry was the smooth pipe, without any corrugations, for the purpose of comparison.

Numerical Model

For the numerical analysis, Computational Fluid Dynamics (CFD) software ANSYS Fluent was used. Fluent is a Finite Volume Method (FVM) solver, which solves for pressure, flow velocity, and heat transfer in this study. The $k-\epsilon$ turbulence model is applied to this simulation, as achieving convergence is relatively simple using this model. This turbulence model is extensively used in academia and industry for research and development purposes. The SIMPLE algorithm is applied as the pressure-velocity coupling scheme in the momentum equation. The residuals are kept lower than 10^{-4} for pressure, velocity, energy, and continuity.

Grid Generation

The discretization software ANSYS Mechanical was used to generate the mesh for the flow simulation. The mesh generation is a crucial step as it determines the computational cost as well as the accuracy of the solution. Usually, an ordered mesh containing hexahedral elements are preferred as they provide a more accurate solution, but the corrugated pipe is a complex geometry. For such complex geometries, a grid containing tetrahedral elements, as shown in Figure 2(a), is easier to generate, and also requires lesser time.

The disturbances in the boundary layer are amplified throughout the flow, and these small disturbances add up to larger effects on velocity, TKE, and pressure distributions. Hence, it is important to capture these disturbances in detail. Inflation layers are added to capture the crucial boundary layer effects through the pipe as shown in Figure 2(b).

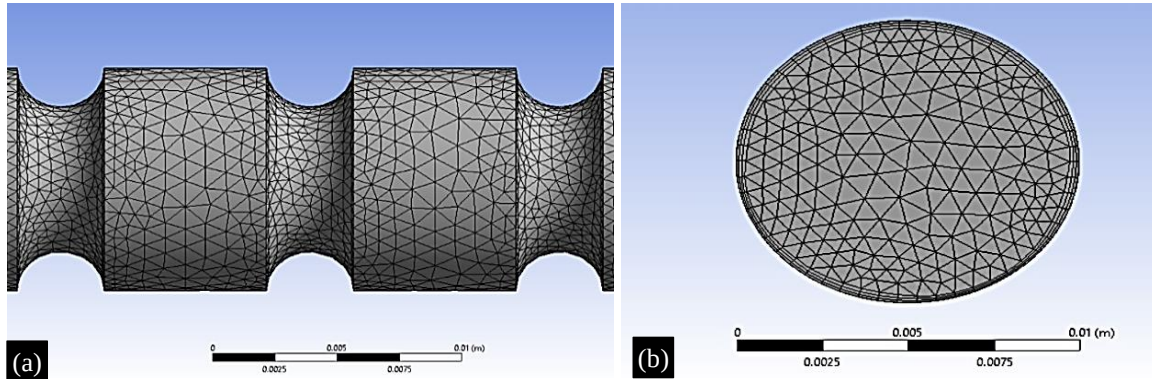


Figure 2. Final Mesh Generated. (a) Tetrahedral elements on pipe mesh. (b) Inflation layers.

Governing Equations

The conservation equations for the fluid flow through a corrugated pipe can be written as shown:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{-\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_i} + \delta_{ij} \right] \quad (2)$$

Energy equation:

$$\frac{\partial}{\partial x_i} (u_i (\rho E + p)) = \frac{-\partial}{\partial x_i} \left[\left(\lambda + \frac{C_p}{Pr_t} \right) - \frac{\partial T}{\partial x_j} + \mu (T_{ij})_{eff} \right] \quad (3)$$

Where, ρ , u , μ , p , λ , C_p and T represent fluid density, velocity flow, dynamic flow viscosity, pressure, thermal conductivity, specific heat, and temperature.

Flow Parameters and Boundary Conditions

The no-slip condition was considered on the walls of the pipe. The working fluid for the simulations was water. The physical properties include a density of 998.2 kg/m^3 , specific heat (C_p) of 4.18 J/kg.K , dynamics viscosity (μ) of 0.001003 kg/(ms) and thermal conductivity (λ) of 0.6 W/kg.K . Temperature at inlet was 298.15 K . The Reynolds number at the inlet was specified as 5000. Boundary conditions are inlet velocity with inlet temperature, and outlet pressure at zero static pressure (P_o).

RESULTS AND DISCUSSIONS

Three models having different corrugated ring diameters (CRD) (1.5, 2.5, and 3.5 mm) were investigated. Figure 3 represents the static pressure along the length of the pipe. As can be observed from the figure, the pressure decreases substantially as the length increases. The flow field is divided into three main regions. The inlet area has a higher pressure, the middle area has a lower pressure, and

finally, the outlet area has the lowest pressure.

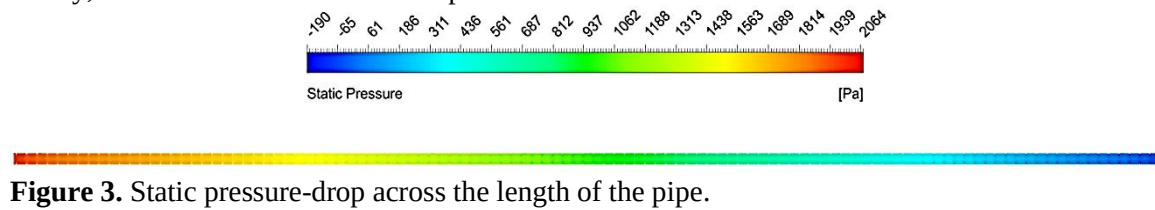


Figure 3. Static pressure-drop across the length of the pipe.

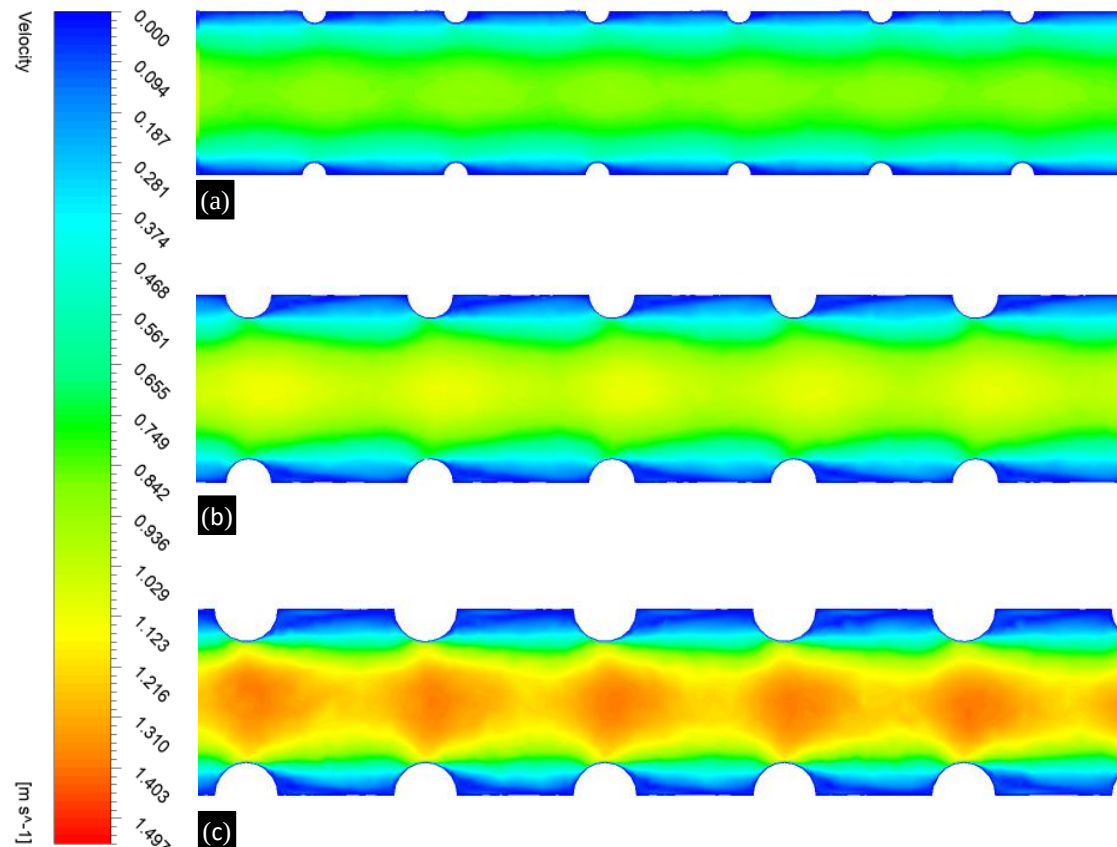


Figure 4. Velocity distribution along the pipe for different CRD values. (a) CRD=1.5 mm; (b) CRD=2.5 mm; (c) CRD=3.5 mm.

Figure 4 shows the velocity distribution contour for different values of CRD. For the smaller value of CRD of 1.5 mm, the local velocity is maximum at the center of the pipe and decreases significantly as one move towards the pipe walls. However, for CRD values of 2.5 and 3.5 mm, the velocity starts to increase even at corrugated ring walls.

In Figure 5, the contours of the turbulent kinetic energy (TKE) are shown for different corrugated ring diameters. It can be seen that the increase in CRD significantly increases the TKE variations in the pipe. This is due to the disturbance caused by the corrugated ring surfaces in the flow direction. The increased variation in TKE suggests that there is better mixing and more turbulence in the flow. This leads to an increase in the Nusselt number, implying an increase in convective heat transfer.

The temperature distribution with different corrugated ring diameters (CRD) is shown in Figure 6. An increase in temperature further away from the wall can be seen with increasing CRD. This is due to more heat being transferred from the wall to the fluid, due to the corrugated rings. The highest temperature in each configuration is on the walls of the pipe. Based on these two observations, it is clear that heat transfer shows a direct correlation with corrugated ring diameter.

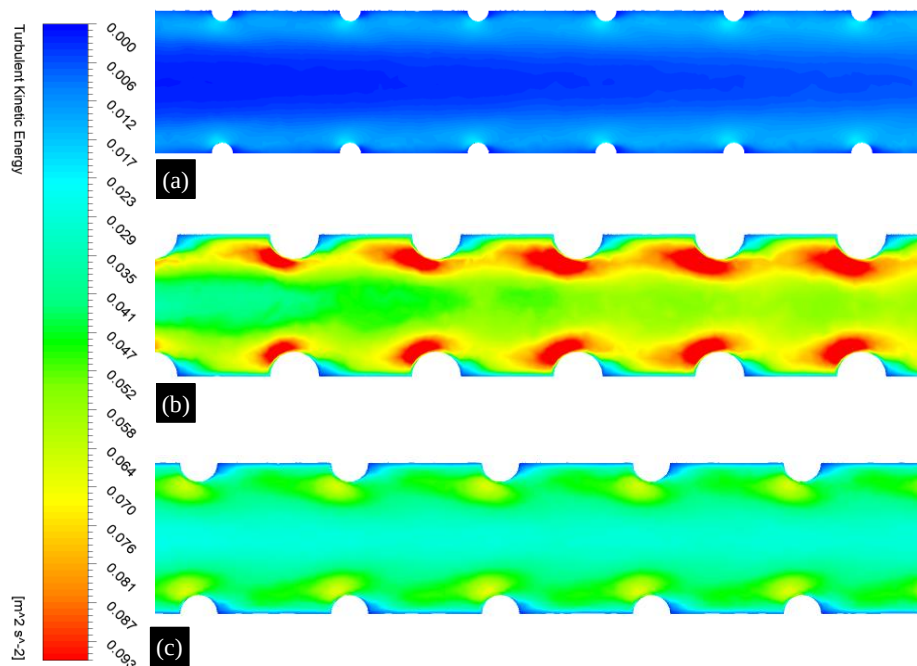


Figure 5. Kinetic energy for different CRD values. (a) CRD=1.5 mm; (b) CRD = 2.5 mm; (c) CRD = 3.5 mm.

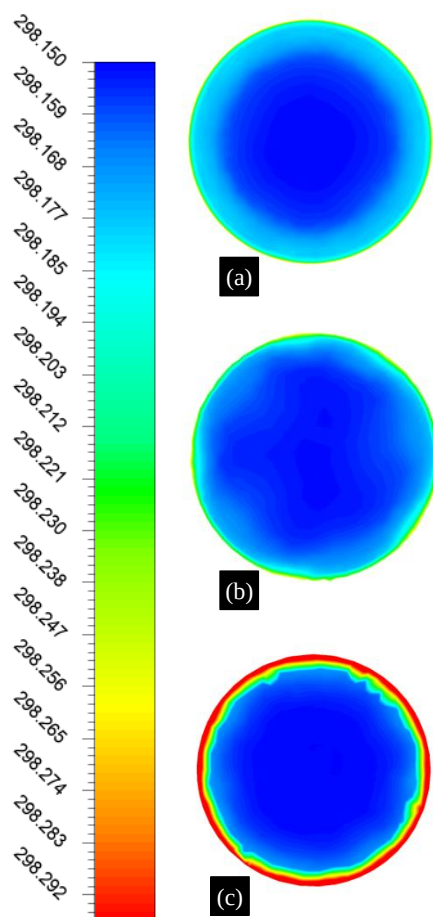


Figure 6. Temperature distribution comparison among different CRD values. (a) CRD = 1.5 mm; (b) CRD = 2.5 mm; (c) CRD = 3.5 mm.

CONCLUSIONS

From the above discussions we can conclude the following:

1. As we increase the diameter of the corrugated ring, the heat transfer coefficient increases and hence there is increase in heat transfer.
2. The increased diameter of the ring increases the disturbance in the flow direction and hence the transverse velocity increases, which leads to greater heat transfer coefficient.

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