Analysis of parallel flow heat exchanger using SiO₂ nanofluids in the laminar flow region

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Abstract. Convective and overall heat transfer coefficients of SiO₂ nanofluid flowing in a concentric DTHE are determined experimentally. The tests are carried out in the 800<Re<1900 range using SiO₂/22nm nanofluids prepared in 0.2, 0.6 and 1.0% volume concentrations in 30:70 ratio glycerol-water mixture base liquid. The thermal and physical properties of silica nanofluids are determined in the range of 20-80°C. Viscosity, thermal conductivity, and density of nanofluids increased with particle concentration whereas specific heat decreased. Thermal conductivity and specific heat of nanofluids increased with temperature while viscosity and density decreased. Heat transfer experiments are conducted using nanofluids at a bulk temperature of 35°C in a laminar developing flow region. Overall heat transfer coefficient and convective HTC of 1.0% silica nanofluids are increased by 21.2 and 36.3% compared to base liquid.

Keywords: Glycerol-water mixture, double tube heat exchanger, overall heat transfer coefficients, SiO₂ nanofluid, developing laminar flow.

1. Introduction

Because of its many uses in the transfer of thermal energy, the determination of forced convection HTC for the flow of liquids like water, ethylene glycol, and lubricants has acquired significance. HTC’s have been determined in single-phase fluid systems for a variety of parameters and operating situations. However, the efficiency of these devices in transporting heat with traditional fluids has reached saturation. The development of novel thermal fluids for improved HT performance has become necessary. HT coefficient improvements contribute to the downsizing of thermal equipment, which has become more essential. Active and passive methods for improving heat transmission were proposed by few authors [1-2].

A passive method for producing nanofluids is the dispersion of nanosized metal or metal oxide particles in a base fluid. Recent research using nanometer-sized particles has shown that heat transfer enhancement may be achieved without a significant rise in pumping capacity needs or other dynamic...
issues. The NF’s have also proven to have improved rheological characteristics, stability, and thermal conductivity.

Compact HE’s are used in a variety of sectors, including automotive, to transfer heat from an IC engine to a sink via a thermal fluid known as coolant. There have been a lot of advancements in this area as a result of the introduction of new technology, including advances in heat dissipation capabilities, size minimization, and greater power production. Heat exchanger efficiency is determined by the qualities and properties of heat transfer fluids. Heat transfer fluid limitations have now reached a point where heat exchanger efficacy is being restricted. Nanofluids are being used in place of traditional fluids to address these constraints [3-4].

Many studies have demonstrated HTC improvements in forced convection with various NF’s moving in a tube under laminar and turbulent flow conditions in the published works. Masuda et al. [5] experimented with the first research on the impact of mixing NP’s of aluminum oxide, silica, and TiO$_2$ in water. They measured the nanofluids’ TC and VST at various temperatures and particle concentrations. At a particle concentration of 4.0 percent at T=67°C, the values of effective TC of Al$_2$O$_3$ and TiO$_2$ NF’s increased by 30% and 10%, respectively. However, at 1.0 percent particle concentration, SiO$_2$ nanofluid exhibited a 1.0 percent increase in heat conductivity. Few writers have provided reviews on the thermal and physical characteristics of NF’s and HTC’s [6-8].

Bontemps et al. [9] evaluated the HTC’s for flow in a tube using SiO$_2$/water(22nm) NF’s under a UWT boundary condition. For ‘φ’= 2.3, 8.0, and 19%, the experiment was conducted at T=15-90°C and Re= 100 to10000. In the turbulent region, they saw a significant rise in HTC compared to water. They discovered that particle concentration affects heat transfer coefficients, whereas the mixing of SiO$_2$ NP’s affects the pressure drop.

Bontemps et al. [10] studied the HTC and pressure reduction of SiO$_2$/water NF’s under a UHF boundary condition in another article. They found the improvements in heat transmission in the laminar range to be negligible. However, up to Re = 10,000, significant improvements in heat transmission have been observed in the turbulent area. When compared to water, the findings showed 30 percent and 100 percent heat transfer improvements with ‘φ’ of 2.3 and 19.0%, respectively.

Ferrouillat et al. [11] experimented to determine the HTC of water/SiO$_2$ (22nm) nanofluid at 20-70°C in the range of 200<Re<10,000. The HT coefficients found at φ=2.3 and 19% are 10 and 50% higher, respectively than the values recorded with water.

Julia et al. [12] conducted HT tests using SiO$_2$ NP’s distributed in water in the turbulent range of Re= 3000 to 100000. At a bulk temperature higher than 60°C, a maximum HTC increase of 300% was recorded at Re = 30,000 using SiO$_2$ NP’s of ‘φ’=5%. Kulkarni et al. [13] carried out tests using SiO$_2$ NP’s dispersed in a 60:40 wt. ratio of EG-water. They examined the impact of particle diameter on viscosity using 20nm, 50nm, and 100nm NP’s of φ= 2% to 10%. Experiments revealed that HTC enhanced as ‘φ’ rises.

The HTC raises with a rise in ‘φ’, according to the research done so far using SiO$_2$ nanofluid. Many authors have reported studies with φ up to 19% and T= 70°C, indicating that the nanofluid is stable at high concentrations and temperatures. There haven’t been any studies including a reduction in HTC using SiO$_2$ NF’s till now. Previous research has shown that particle size has little effect on convective HTC’s. Furthermore, the highest HTC enhancement is seen in the turbulent Reynolds Number range.

A variety of conventional fluids are available for maintaining the heat exchanger's performance. Throughout the past couple of centuries, distilled water and water-EG mixture have been utilized as
coolants. When combined with water, glycerol is emerging as a viable option since it may be utilized as a base liquid to create stable nanofluids. The characteristics of nanofluids are significantly influenced by the properties of the base liquid and the properties of the distributed nanoparticles. Studies in the laminar flow area of GW70 utilizing SiO$_2$ nanofluids have not been described in the literature, therefore this study was undertaken. Glycerol-water mixture in 30:70 by volume, referred to as GW70, is used as the base liquid in this work. SiO$_2$ nanoparticles of a mean diameter of 22nm are dispersed in GW70 in three concentrations of 0.2, 0.6 and 1.0%.

2. Methodology

2.1. Preparation of nanofluids

NF’s of φ= 0.2, 0.6, and 1.0% concentrations were made using dispersion synthesis of SiO$_2$ (mean size of 22nm) NP’s in a glycerol-water (30:70) mixed solution. Without adding any surfactant, the produced nanofluids were shown to be stable for four weeks. The particle concentration (∅) required for a certain amount of ‘φ’ was calculated using Eq. (1).

$$\bar{\phi} = \frac{w \rho_{bf}}{(1-w) \rho_p + \frac{w}{100} \rho_{bf}}$$ (1)

Where ∅ is particle concentration %, w is weight, $\rho_p$ and $\rho_{bf}$ are the densities of particle and base liquid.

The TPS 500S thermal constants analyzer was utilized to determine the thermal diffusivity, thermal conductivity, and specific heat of NF’s. A Brookfield Viscometer was utilized to measure the VST of nanofluids. The density of nanofluids is calculated from measured values of “thermal conductivity, viscosity, and specific heat”. Properties of NF’s and base liquid measured in the range of 20-80°C are listed in Table 1.

| Property   | Temp., (°C) | φ=0.0(%) | φ=0.2(%) | φ=0.6(%) | φ=1.0(%) |
|------------|-------------|----------|----------|----------|----------|
| $\mu$, cP  | 20          | 3.040    | 3.084    | 3.357    | 3.615    |
|            | 40          | 1.840    | 1.935    | 2.173    | 2.337    |
|            | 60          | 1.116    | 1.220    | 1.370    | 1.471    |
|            | 80          | 0.677    | 0.759    | 0.857    | 0.919    |
|            | 20          | 0.460    | 0.488    | 0.568    | 0.672    |
| $k$, W/mK  | 40          | 0.485    | 0.595    | 0.688    | 0.786    |
|            | 60          | 0.510    | 0.616    | 0.726    | 0.856    |
|            | 80          | 0.530    | 0.651    | 0.774    | 0.908    |
|            | 20          | 0.3510   | 3468     | 3448     | 3436     |
| $C_p$, J/kgK | 40         | 3516     | 3524     | 3504     | 3488     |
|            | 60          | 3622     | 3586     | 3572     | 3546     |
|            | 80          | 3686     | 3652     | 3645     | 3601     |
|            | 20          | 1044     | 1048     | 1054     | 1057     |
| $\rho$, kg/m$^3$ | 40      | 1033     | 1037     | 1043     | 1048     |
|            | 60          | 1024     | 1028     | 1034     | 1032     |
|            | 80          | 1013     | 1018     | 1026     | 1028     |
2.2. *Experiments using Parallel Flow DTHE*

A parallel flow DTHE (L = 0.5mm; Di = 0.17; di = 0.1.m) was used as the test section as shown in Figure 1. The thickness of the tube material (copper) is 0.027m. The annulus is supplied with nanofluids, while the tube is with hot water. Thermocouples are used to measure the temperatures at the inlet and exit. To prevent heat loss to the environment, the outside tube is insulated. To maintain the fluid at the correct temperature, a cooling chamber and a thermostat are used. The temperature of the hot water is controlled by an electric heater and a thermostat. The temperature and flow rates of hot water and nano-fluid effect the estimated Nusselt number. For each cycle of testing, an average of three readings is obtained to minimize errors. Flow meters are installed at the entrance and exit of the tubes to control and monitor the flow rate. Experiments using glycerol-water base liquid and silica nanofluids are carried out in parallel flow settings at mass flow rates of 0.030, 0.026, and 0.017 kg/s. The average temperatures of the tube and annulus liquids are close to 60°C and 35°C, respectively. After the system has reached the study state, the readings are recorded. During the test, the mass flow rate of nanofluids and hot water, as well as their input and exit temperatures, are recorded.

3. *Data Reduction*

3.1. *Equations to derive HTC, NTU and effectiveness*

HTC’s are calculated using standard equations from the literature and data books and are shown as Eqs. (2)-(13)

\[ Q_h = m_h \cdot C_{ph} \cdot (T_{hi} - T_{ho}) \tag{2} \]

\[ D_h = \frac{4 \text{ times cross-sectional area}}{\text{Wetted perimeter}} = \left( \frac{D_i^2 - d_o^2}{d_o} \right) \tag{3} \]
\[ \text{Re} = \left( \frac{\rho v D_h}{\mu} \right) \]  \hspace{1cm} (4)

\[ \text{Pr} = \left( \frac{\mu C_p}{k} \right) \]  \hspace{1cm} (5)

\[ \text{Nu} = \frac{h X D_h}{k} \]  \hspace{1cm} (6)

\[ \frac{h A_i}{A_o} = \frac{h d_1}{d_o} = h_A \]  \hspace{1cm} (7)

Where \( A_o = \pi L d_o \) and \( A_i = \pi L d_i \), \( h_A \) = HTC over common surface area

\[ Q_c = m_c C_{pc} (T_{co} - T_{ci}) \]  \hspace{1cm} (8)

The logarithmic mean temperature difference, LMTD = \[
\frac{\Delta T_1 - \Delta T_2}{\ln \left( \frac{\Delta T_1}{\Delta T_2} \right)}
\]  \hspace{1cm} (9)

Where \( \Delta T_1 = T_{hi} - T_{ci} \); \( \Delta T_2 = T_{ho} - T_{co} \);

\[ U_o = \frac{Q_c E}{A_o \left( \frac{\Delta T_1 - \Delta T_2}{\ln \left( \frac{\Delta T_1}{\Delta T_2} \right)} \right)} \]  \hspace{1cm} (10)

\[ \frac{1}{h_{nf}} = \frac{1}{U_o} - \frac{1}{h_A} \]  \hspace{1cm} (11)

\[ \text{NTU} = \frac{U A}{C_{\text{min}}} = \frac{Q_c E}{\text{LMTD} \times C_{\text{min}}} \]  \hspace{1cm} (12)

The effectiveness of the HE is given by,
\[ \varepsilon = \frac{1 - \exp[-\text{NTU}(1-Z)]}{1 - Z \exp[-\text{NTU}(1-Z)]} = \frac{q}{q_{\text{max}}} \]  \hspace{1cm} (13)

Where \( q = C_h (T_{hi} - T_{ho}) = C_c (T_{co} - T_{ci}) \); \( Z = \frac{C_{\text{min}}}{C_{\text{max}}} \); \( C_{\text{min}} \) is smaller of heat capacities of hot and cold fluids; and \( q_{\text{max}} = C(T_{hi} - T_{ci}) \).

3.2. Validation of HTC’s:

The tests were first carried out using water at various flow rates (1500<Re<5500). The water in the inner pipe is kept nearer to a temperature of 60°C, while the water in the annulus is kept at 35°C. Because the length of the HE is short, flow rates of (680<Re<1900) in the annulus utilizing nanofluids and base liquid dropped into the developing laminar area. Surface temperatures are calculated using conventional formulae from data books, and energy balance is confirmed on both the hot and cold sides using Newton’s law.

Eq. (14) proposed by Gnielinski [14] is used to calculate the Nu numbers of water flowing through the tube for 2300<Re<10^6, 0.5<Pr<2000. The collected data were compared and verified with Eq. (15) proposed by Taler [15] for a flow in a tube under UHF boundary conditions, and the values were in close agreement, as shown in Table 2.
Nu = \left[ \frac{\left( \frac{1}{2} \right) (Re-1000)Pr}{0.07 + 12.7 \left( \frac{1}{2} \right)^{0.65} (Pr^{2/3} - 1)} \right] \left[ 1 + \left( \frac{Dh}{L} \right)^{2/3} \right] \left[ \frac{\mu}{\mu_s} \right]^{0.11} \quad (14)

\text{and } f = \left[ 1.58 \ln(Re) - 3.82 \right]^{-2}

Nu = \text{Nu}_{m,q} (Re = 2300) + \left[ \frac{\left( \frac{1}{2} \right) (Re-2300)^{1.008}}{1.08 + 12.39 \left( \frac{1}{2} \right)^{0.65} (Pr^{2/3} - 1)} \right] \left[ 1 + \left( \frac{Dh}{L} \right)^{2/3} \right] \left( \frac{Pr}{Pr_s} \right)^{0.11} \quad (15)

Valid for 2300 \leq Re \leq 10^6 ; 0.1 \leq Pr \leq 1000 ; \left( \frac{Dh}{L} \right) \leq 1

Where \text{Nu}_{m,q} is mean Nusselt number estimated for a combined developing flow in a tube.

Experiments are carried out with base liquid and nanofluids flowing in the annulus, with the flow rates of hot water in the tube remaining constant. The base liquid and nanofluids then flow in the annulus at three different flow rates in experiments. HTC was calculated across a shared surface area. The LMTD, \(U_0\), and Nu values are computed. For most nanofluid concentrations, the flow resulted in the laminar zone, suggesting simultaneous development of the hydrodynamical and thermal boundary layer thickness.

The experimental Nu number of nanofluids and base liquid is compared and verified with Eq. (16) developed by Taler [15], valid for “thermally and hydrodynamically developing flow”. The experimental data is in close agreement with Eq. (16) with a maximum deviation of 1.38 %.

\text{Nu}_{m,q} = \left[ \text{Nu}_{m,q1}^3 + 0.63 + \left( \text{Nu}_{m,q2} - 0.6 \right)^3 + \text{Nu}_{m,q3}^3 \right]^{1/3} \quad (16)

Where \text{Nu}_{m,q1} = \frac{48}{11} = 4.364 \quad (16a)

\text{Nu}_{m,q2} = 1.953 \left( \text{RePr} \frac{Dh}{L} \right)^{1/3} \quad (16b)

\text{Nu}_{m,q3} = 0.924 \text{Pr}^{1/3} \left( \text{RePr} \frac{Dh}{L} \right)^{1/2} \quad (16c)

Eqs. (12) and (13) are used to calculate NTU and the effectiveness of HE. Both the tube and annulus sides' Re, hA, and Nu numbers are shown in Table 2. The \(U_0\), \(h_{nf}\), NTU, and effectiveness of the HE are also listed.
Table 2. NTU, effectiveness and validation of heat transfer coefficients

| Sl. No. | Water flow kg/s | Re Eq. 4 | $h_A$ Eq. 14 | Nu Eq. 14 | Nu Eq. 15 | Liquid Flow kg/s | Re Eq. 4 | $U_o$ Eq. 10 | $h_{df}$ Eq. 11 | Nu Eq. Exp. Eq.6 | Nu Eq. 16 | NTU Eq. 12 | Efft. Eq. 13 |
|---------|-----------------|----------|--------------|-----------|-----------|------------------|----------|--------------|----------------|----------------|-------------|-------------|--------------|
| 1       | 0.02            | 5296     | 1824         | 35.59     | 35.15     | 0.02             | 3723     | 571.8        | 832.9          | 13.31          | 13.24       | 0.14        | 0.12         |
| 2       | 0.017           | 4723     | 1595         | 30.95     | 30.51     | 0.017           | 3165     | 523.8        | 779.9          | 12.46          | 12.21       | 0.15        | 0.13         |
| 3       | 0.0085          | 2519     | 747          | 14.40     | 13.39     | 0.0085          | 1582     | 333.8        | 603.4          | 9.64           | 8.63        | 0.19        | 0.16         |
| 4       | 0.02            | 5296     | 1822         | 35.56     | 35.13     | 0.03             | 5584     | 624.2        | 949.4          | 15.17          | 16.21       | 0.15        | 0.13         |
| 5       | 0.017           | 4724     | 1594         | 30.94     | 30.51     | 0.0255           | 4524     | 561.9        | 867.7          | 13.94          | 14.86       | 0.16        | 0.14         |
| 6       | 0.0085          | 2513     | 745          | 14.35     | 13.36     | 0.017            | 3004     | 370.4        | 737.0          | 11.84          | 12.13       | 0.21        | 0.18         |
| 7       | 0.02            | 5299     | 1708         | 33.32     | 35.07     | 0.03             | 1897     | 577.7        | 873.1          | 18.47          | 18.84       | 0.14        | 0.12         |
| 8       | 0.017           | 4722     | 1500         | 29.11     | 30.49     | 0.0255           | 1598     | 530.0        | 819.8          | 17.48          | 17.67       | 0.15        | 0.13         |
| 9       | 0.0085          | 2517     | 709          | 13.67     | 13.39     | 0.017            | 1056     | 352.4        | 700.3          | 14.90          | 15.02       | 0.20        | 0.17         |
| 10      | 0.02            | 5337     | 1716         | 33.45     | 35.17     | 0.03             | 1785     | 630.5        | 996.6          | 17.86          | 17.72       | 0.15        | 0.13         |
| 11      | 0.017           | 4620     | 1476         | 28.72     | 30.05     | 0.0255           | 1507     | 567.6        | 922.0          | 16.55          | 16.59       | 0.16        | 0.14         |
| 12      | 0.0085          | 2400     | 672          | 13.01     | 12.58     | 0.017            | 976      | 361.5        | 783.0          | 14.15          | 14.14       | 0.20        | 0.17         |
| 13      | 0.02            | 5275     | 1702         | 33.23     | 34.92     | 0.03             | 1623     | 663.5        | 1087.1         | 16.72          | 16.69       | 0.16        | 0.14         |
| 14      | 0.017           | 4630     | 1479         | 28.76     | 30.08     | 0.0255           | 1377     | 600.7        | 1011.6         | 15.57          | 15.64       | 0.17        | 0.15         |
| 15      | 0.0085          | 2349     | 655          | 12.71     | 12.22     | 0.017            | 913      | 372.0        | 861.8          | 13.28          | 13.33       | 0.21        | 0.18         |
| 16      | 0.02            | 5263     | 1700         | 33.19     | 34.87     | 0.03             | 1501     | 700.1        | 1190.3         | 15.67          | 15.73       | 0.17        | 0.15         |
| 17      | 0.017           | 4642     | 1481         | 28.81     | 30.11     | 0.0255           | 1250     | 634.3        | 1109.1         | 14.67          | 14.74       | 0.18        | 0.15         |
| 18      | 0.0085          | 2417     | 677          | 13.11     | 12.71     | 0.017            | 848      | 394.1        | 942.1          | 12.41          | 12.58       | 0.22        | 0.19         |

4. Results and Discussion

4.1. FESEM AND EDX

The surface morphology and the size of SiO$_2$ nanoparticles are determined by using the FESEM. The morphology of the nanoparticles is shown in Figure 2. Spherical-shaped nanoparticles can be observed for silica nanoparticles and the mean diameter is obtained as 22nm.

4.2. Thermo-physical properties of nanofluids

Table 1 shows the data for thermophysical characteristics such as “viscosity, thermal conductivity, specific heat, and density”. Nanofluids’ TC increased with particle concentration and temperature. VST and density decreased with temperature and increased with concentration. Their specific heat increased with temperature and decreased with concentration.
4.3. Overall heat transfer coefficient and convective HTC of nanofluids

Figure 3 depicts the variation of $U_o$ and $h_{nf}$ at the three flow velocities. The $U_o$ and $h_{nf}$ rose as the flow rate and concentration increased. At a flow velocity of 0.030kg/s, using 1.0 percent silica nanofluids, a maximum augmentation of 21.2% and 36.3% in the $U_o$ and $h_{nf}$ was recorded. Improved heat transfer coefficients are achieved by increasing the TC of nanofluids owing to the increased surface area of nanoparticles, particle rearrangement, and “change of the thermal boundary layer due to the presence of nanoparticles”. Lahari et al. [20] observed a similar pattern in their work.

4.4. Nu number and Re

The Nusselt number rises with Reynolds number, as seen in Fig. 4. Throughout the experiment, flow rates of 0.017, 0.026, and 0.030 kg/s are maintained, and the corresponding Re for the base liquid and nanofluids is calculated. For base liquid, the Reynolds numbers are 1056, 1598, and 1897, respectively. Reynolds numbers for silica nanofluid concentrations range from 840 to 1800. Nanofluid has a lower Nusselt number than the base liquid due to its greater thermal conductivity, which rises with concentration.

4.5. NTU and effectiveness

The data in Table 2 show that the dispersed nanoparticles in the BL enhance the HE's performance. NTU and effectiveness of silica nanofluids increased by 17.5% and 15.5%, respectively, at 1.0 percent concentration and 0.03kg/s flow rate. A similar trend was observed in the published works by previous authors using different nanofluids [16].
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5. Conclusion
Using silica nanofluids produced in a glycerol-water (30:70 ratio by vol.) base liquid, Nu, HTC, and $U_o$ were experimentally investigated. Experiments are conducted in a short-length DTHE under parallel flow circumstances at an average bulk temperature of 35°C. Nanofluids substantially improve the heat exchanger's effectiveness and NTU when compared to base liquid. As the nanofluid concentration and flow rate increased, the HTC improved. The Nusselt number increases as the flow rate and Reynolds number increase. Using nanofluids, a maximum improvement of 36.3 percent and 21.2 percent were found in HTC and $U_o$. When compared to base liquid, NTU and effectiveness enhanced by 17.5% and 15.5%, respectively, suggesting better heat exchanger performance.
Acknowledgments

The first author thanks the R&I Council of REVA University, Bangalore and Department of Mechanical Engineering, Malla Reddy College of Engineering and Technology (Autonomous), Hyderabad, for their support.

Nomenclature

| Symbol | Definition |
|--------|------------|
| A      | Area, m²   |
| BL     | Base liquid |
| Cₚ     | Specific heat, J/Kg K |
| Dₜ     | Hydraulic diameter, m |
| D      | Diameter of the outer tube |
| DTHE   | Double tube heat exchanger |
| f      | Friction |
| HE     | Heat Exchanger |
| HT     | Heat Transfer |
| HTC or h | Convective heat transfer coefficient |
| ID     | Inner diameter of the tube |
| k      | Thermal conductivity, W/mK |
| L      | Length of the tube, m |
| NF/NP  | Nano Fluid/Nanoparticle |
| Nu     | Nusselt number, Nu=hd/k |
| NTU    | Number of transfer units |
| OD     | Outer diameter of the tube |
| Pr     | Prandtl number, Pr=Cₚµ/k |
| Q      | Heat transfer rate, W |
| Re     | Reynolds number |

Greek symbols

| Symbol | Definition |
|--------|------------|
| µ      | Dynamic viscosity, cP |
| ρ      | Density of fluid, Kg/m³ |
| φ      | Volume concentration |
| α      | Thermal diffusivity |
| ε      | Effectiveness of HE |

Subscripts

| Symbol | Definition |
|--------|------------|
| NF/NP  | Nano Fluid/Nanoparticle |
| ci     | Cold inlet |
| co     | Cold outlet |
| h      | Hot |
| hi     | Hot inlet |
| ho     | Hot outlet |
| nf     | Nanofluid |

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