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Heat Transfer Enhancement in Cross Flow Heat Exchangers Using Oval Tubes and Multiple Delta Winglets

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Abstract: ***A heat exchanger consists of heat transfer elements such as a core or matrix containing the heat transfer surface, and fluid distribution elements such as headers, manifolds, tanks, inlet and outlet nozzles or pipes, or seals. Usually, there are no moving parts in a heat exchanger; however, there are exceptions, such as a rotary regenerative exchanger (in which the matrix is mechanically driven to rotate at some design speed) or a scraped surface heat exchanger. The heat transfer surface is a surface of the exchanger core that is in direct contact with fluids and through which heat is transferred by conduction. That portion of the surface that is in direct contact with both the hot and cold fluids and transfers heat between them is referred to as the primary or direct surface. To increase the heat transfer area, appendages may be intimately connected to the primary surface to provide an extended, secondary, or indirect surface. These extended surface elements are referred to as fins. Thus, heat is conducted through the fin and connected (and/or radiated) from the fin (through the surface area) to the surrounding fluid, or vice versa, depending on whether the fin is being cooled or heated. As a result, the addition of fins to the primary surface reduces the thermal resistance on that side and thereby increases the total heat transfer from the surface for the same temperature difference. Fins may form flow passages for the individual fluids but do not separate the two (or more) fluids of the exchanger. These secondary surfaces or fins may also be introduced primarily for structural strength purposes or to provide thorough mixing of a highly viscous liquid. Not only are heat exchangers often used in the process, power, petroleum, transportation, air-conditioning, refrigeration, cryogenic, heat recovery, alternative fuel, and manufacturing industries, they also serve as key components of many industrial products available in the marketplace. These exchangers can be classified in many different ways. They are classified according to transfer processes, number of fluids, and heat transfer mechanisms. Conventional heat exchangers are further classified according to construction type and flow arrangements. Another arbitrary classification can be made, based on the heat transfer surface area/volume ratio, into compact and non-compact heat exchangers. This classification is made because the type of equipment, fields of applications, and design techniques generally differ.***

Keywords: Heat transfer enhancement, oval-tubes, Delta winglets, cross flow heat exchangers

1. Introduction to Heat Exchangers

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact. In heat exchangers, there are usually no external heat and work interactions. Typical applications involve heating or cooling of a fluid stream of concern and evaporation or condensation of single or multicomponent fluid streams. In other applications, the objective may be to recover or reject heat, or sterilize, pasteurize, fractionate, distill, concentrate, crystallize, or control a process fluid. In a few heat exchangers, the fluids exchanging heat are in direct contact. In most heat exchangers, heat transfer between fluids takes place through a separating wall or into and out of a wall in a transient manner. In many heat exchangers, the fluids are separated by a heat transfer surface, and ideally they do not mix or leak. Such exchangers are referred to as direct transfer type, or simply recuperators. In contrast, exchangers in which there is intermittent heat exchange between the hot and cold fluids—via thermal energy storage and release through the exchanger surface or matrix are referred to as indirect transfer type, or simply regenerators. Such exchangers usually have fluid leakage from one fluid stream to the other, due to pressure differences and matrix rotation/valve switching. Common examples of heat exchangers are shell-and tube exchangers, automobile radiators, condensers, evaporators, air pre-heaters, and cooling towers. If no phase change occurs in any of the fluids in the exchanger, it is sometimes referred to as a sensible heat exchanger. There could be internal thermal energy sources in the exchangers, such as in electric heaters and nuclear fuel elements. Combustion and chemical reaction may take place within the exchanger, such as in boilers, fired heaters, and fluidized-bed exchangers. Mechanical devices may be used in some exchangers such as in scraped surface exchangers, agitated vessels, and stirred tank reactors. Heat transfer in the separating wall of a recuperator generally takes place by conduction. However, in a heat pipe heat exchanger, the heat pipe not only acts as a separating wall, but also facilitates the transfer of heat by condensation, evaporation, and conduction of the working fluid inside the heat pipe. In general, if the fluids are immiscible, the separating wall may be eliminated, and the interface between the fluids replaces a heat transfer surface, as in a direct-contact heat exchanger.

A heat exchanger consists of heat transfer elements such as a core or matrix containing the heat transfer surface, and fluid distribution elements such as headers, manifolds, tanks, inlet and outlet nozzles or pipes, or seals. Usually, there are no moving parts in a heat exchanger; however, there are exceptions, such as a rotary regenerative exchanger (in which the matrix is mechanically driven to rotate at some design speed) or a scraped surface heat exchanger. The heat transfer surface is a surface of the exchanger core that is in direct contact with fluids and through which heat is transferred by conduction. That portion of the surface that is in direct contact with both the hot and cold fluids and transfers heat between them is referred to as the primary or direct surface. To increase the heat transfer area, appendages may be intimately connected to the primary surface to provide an extended, secondary, or indirect surface. These extended surface elements are referred to as fins. Thus, heat is conducted through the fin and convected (and/or radiated) from the fin (through the surface area) to the surrounding fluid, or vice versa, depending on whether the fin is being cooled or heated. As a result, the addition of fins to the primary surface reduces the thermal resistance on that side and thereby increases the total heat transfer from the surface for the same temperature difference. Fins may form flow passages for the individual fluids but do not separate the two (or more) fluids of the exchanger. These secondary surfaces or fins may also be introduced primarily for structural strength purposes or to provide thorough mixing of a highly viscous liquid. Not only are heat exchangers often used in the process, power, petroleum, transportation, air-conditioning, refrigeration, cryogenic, heat recovery, alternative fuel, and manufacturing industries, they also serve as key components of many industrial products available in the marketplace. These exchangers can be classified in many different ways. They are classified according to transfer processes, number of fluids, and heat transfer mechanisms. Conventional heat exchangers are further classified according to construction type and flow arrangements. Another arbitrary classification can be made, based onthe heat transfer surface area/volume ratio, into compact and non-compact heat exchangers.

1.1 Heat Exchanger Types

Heat exchangers are typically classified according to flow arrangement and type of construction. In this introductory treatment, we will consider three types that are representative of a wide variety of exchangers used in industrial practice. The simplest heat exchanger is one for which the hot and cold fluids flow in the same or opposite directions in a concentric-tube(or double-pipe) construction. In the parallel-flow arrangement of Figure 1.2a, the hot and cold fluids enter at the same end, flow in the same direction, and leave at the same end. In the counter flow arrangement, Figure 1.2b, the fluids enter at opposite ends, flow in opposite directions, and leave at opposite ends. A common configuration for power plant and large industrial applications is the shell-and-tube heat exchanger**,** shown in Figure 1.2c. This exchanger has one shell with multiple tubes, but the flow makes one pass through the shell. Baffles are usually installed to increase the convection coefficient of the shell side by inducing turbulence and a cross-flow velocity component. The cross-flow heat exchanger**,** Figure 1.2d, is constructed with a stack of thin plates bonded to a series of parallel tubes. The plates function as fins to enhance convection heat transfer and to ensure cross-flow over the tubes. Usually it is a gas that flows over the fin surfaces and the tubes, while a liquid flows in the tube. Such exchangers are used for air-conditioner and refrigeration heat rejection applications.

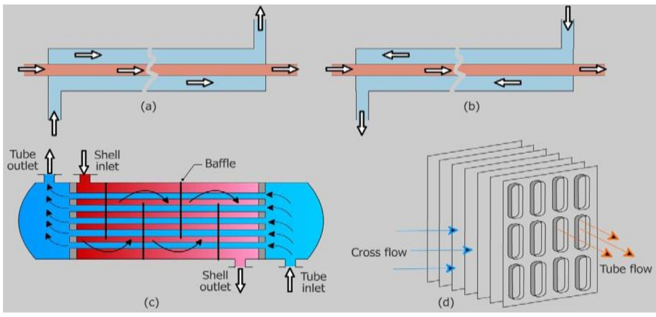

Figure 1.2: Types of heat exchangers – (a) concentric-tube parallel-flow; (b) concentric-tube counter-flow; (c) shell-and-tube; and (d) cross flow.

A cross-flow heat exchanger exchanges thermal energy from one airstream to another in an air handling unit (AHU). Unlike a rotary heat exchanger, a cross-flow heat exchanger does not exchange humidity and there is no risk of short-circuiting the airstreams. A cross-flow heat exchanger is used in a cooling and ventilation system that requires heat to be transferred from one airstream to another. A cross-flow heat exchanger is made of thin metal panels, normally aluminum. The thermal energy is exchanged via the panels. A traditional cross-flow heat exchanger has a square cross-section. It has a thermal efficiency of 40–65%. A counter-flow or dual cross-flow heat exchanger can be used if greater thermal efficiencies are required – typically upto75–85%. In some types of exchanger, humid air may cool down to freezing point, forming ice. A cross-flow is typically less expensive than other types of heat exchanger. It is normally used where hygienic standards require that both airstreams are kept completely separate from one another. It is often used in heat recovery installations in large canteens, hospitals and in the food industry. Unlike a rotary heat exchanger, a cross-flow heat exchanger does not exchange humidity.

The basic designs for heat exchangers are the shell-and-tube heat exchanger and the plate heat exchanger, although many other configurations have been developed. According to flow layout, heat exchangers are grouped in:

- Shell-and-tube heat exchanger (STHE), where one flow goes along a bunch of tubes and the other within an outer shell, parallel to the tubes, or in cross-flow (Fig. 1.3a shows a typical example of STHE; details presented below).
- Plate heat exchanger (PHE), where corrugated plates are held in contact and the two fluids flow separately along adjacent channels in the corrugation (Fig. 1.3 b shows details of the interior of a PHE; more details are presented below).
- Open-flow heat exchanger, where one of the flows is not confined within the equipment (or at least, like in Fig. 1.3 c, not specifically piped). They originate from air-cooled tube-banks, and are mainly used for final heat release from a liquid to ambient air, as in the car radiator, but also used in vaporizers and condensers in air-conditioning and refrigeration applications, and in directly-fired home water heaters. When gases flow along both sides, the overall heat-transfer coefficient is very poor, and the best solution is to make use of heat-pipes as intermediate heat-transfer devices between the gas streams; otherwise, finned

separating surfaces, or, better, direct contact through a solid recuperator, are used.

- Contact heat exchanger, where the two fluids enter into direct contact (simultaneous heat and mass transfer takes place). Furthermore, the contact can be continuous, i.e. when the two fluids mix together and then separate by gravity forces, as in a cooling tower, or the contact can be alternatively with a third medium, usually solid, as in regenerative heat exchangers (RHE), like the rotating wheel shown in Fig. 1.3 d (the hot gas heats the wheel whereas the cold gas retrieves that energy). When the heat-exchange process between the hot and the cold fluids is delayed significantly, the term 'thermal energy storage' is used instead of RGE. There is always some contamination by entrainment of one fluid by the other, although many times it is irrelevant (as in air-conditioning heat-recuperators), or even intended (as in cooling towers). Notice also that, if the mixed-up fluids do not separate, as in open feed-water heaters or in evaporative coolers, the device is not named heat exchanger but just heater or cooler.

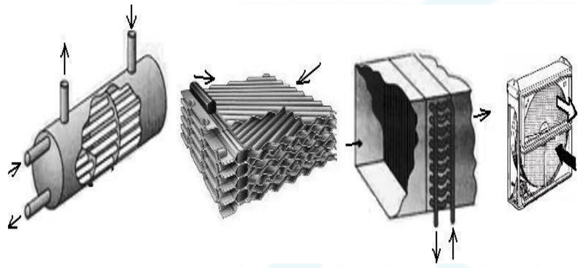

Figure 1.3: Types of heat exchangers: a) shell-and-tube, b) plates, c) open-flow, d) rotating-wheel.

Additionally, heat exchangers may be classified according to the type of fluid used (liquid-to-liquid, liquid-to-gas, gas-to-liquid, gas-to-gas), according to phase changes (vaporizers, condensers), according to relative flow direction (counter-flow, co-flow, cross-flow), according to area density (transfer area per unit volume) or channel size, etc. in terms of the smallest hydraulic diameter of the two flows. Heat exchangers are used to promote thermal energy flows at intermediate stages in process engineering, or as a final heat release to the environment, ambient air in most cases, which renders non-contact devices as STHE and PHE) rather inefficient and recourse is to be made of contact heat exchangers as the wet cooling towers treated aside. A special case is that of marine engineering, where seawater is plenty available in the environment, greatly alleviating the thermal problem for heat-exchangers, but at a cost in materials compatibility (cupro-nickel or titanium must be used instead of copper or aluminium), since seawater is very corrosive and plenty of microorganisms. In order to mitigate the effects of seawater on heat exchangers, and to minimize hull-pass-troughs, only one central heat exchanger is cooled by seawater (a PHE usually), and all other required heat exchangers use clean fresh-water as an intermediate fluid loop to finally discharge the energy at the seawater exchanger (centralized cooling system); different fluid loop layouts can be used, normally grouping several thermal loads by proximity of location and by temperature level. For the latter, two levels are considered: high-temperature level (HT-circuit), say at >50 ºC like for engine cooling circuits (main engine and auxiliaries), and low-temperature level (LT-circuit), say at <50 ºC like for engine-oil-lubrication cooling, air-conditioners and refrigerators, electronic equipment, and so on; instead connecting the HT-circuit to the LT-circuit by means of a heat exchanger, it is better to use a partial mixing of the streams (regulated by a thermostatic valve). The standard design value for final heat release in ships is a seawater temperature of 32 ºC, to allow for operation in all seas, in spite of fact that the largest share of operating time for most ships takes place in seas at 15 ºC to 20 ºC (initial cost cannot be avoided, but operation costs can be minimized by adjusting the seawater flow). Heat exchangers are widely used in process control to promote or quench chemical reactions (by heating or cooling, respectively). The food industry makes use of heating to kill pathogen microorganisms (sterilization), either after canning, or before packaging; the latter is most conveniently made for liquid stuff in heat exchangers. Sterilization, i.e. the inactivation of all microorganisms, requires high-temperature processing, typically at 120 ºC or more (i.e. under pressure, for aqueous stuff); to kill even the most resistant spores. In the pasteurization process, however, a quick heating to 60 ºC or 70 ºC is applied to kill most bacteria without protein denaturizing, but other microorganisms remain, what implies that quick cooling after pasteurization is required (what makes heat pumps so convenient), and that vacuum or refrigeration is needed afterwards. The time-for-pasteurization (or for sterilization) depends on the microorganisms and the holding temperature; tabulated values are usually given for a processing temperature of $T0$=120 ºC, and can be extrapolated to other temperatures with the logarithmic law with $m\approx 1$

1.2 Heat exchanger analysis

The thermal analysis of a heat exchanger is based on the simple coaxial configuration (Fig.1.6), where one fluid goes along a pipe, and the other fluid goes along the annular section within a larger cylindrical sheath with openings at the ends, and in particular, to the counter-current configuration shown in Fig. 1.6 a, more thermally-efficient than the co-flow set-up of Fig. 1.6b. The coaxial cross-section is sketched in Fig. 1.6c. longitudinal temperature-profiles for the counter-flow and the co-flow configurations are also shown and a detail of the transversal temperature profile across the wall separating the two fluids (Fig. 1.6d). The minimum temperature jump from one fluid to the other is called the (temperature) ‘approach’ of the heat exchanger.

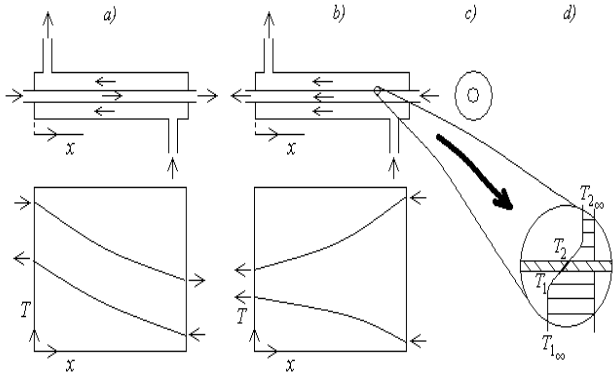

Figure 1.6: Simple annular heat exchangers: a) sketch and temperature profile in a counter-flow configuration, b) sketch

and temperature profile in co-flow, c) cross-section sketch, d) detail across the separating surface.

Heat transfer from one fluid to the other is a combined convection-conduction-convection process across the separating surface, as detailed in Fig. 1.6d, where the hotter fluid is subscripted '1' and the colder one '2'. The fact that the colder flow surrounds the hotter one in Fig. 1.6 is irrelevant to the results here developed, although it may be advantageous in practice to minimize heat-losses to the ambient (if its temperature difference to the ambient is lower than that of the hotter one), here neglected.

2. Physical Modeling

The plan-view representation of the computational domain is shown in Fig. 3.1the dimensions used are those of a proposed design being reported elsewhere by the authors. Two neighboring fins form a channel of height H, width B ¼ 11:25H and length L ¼ 13:75H. The built-in oval tube, of semi-major diameter a ¼ 4:40Hand semi-minor diameter b ¼ 1:465H, is located at a distance L1 ¼ 6:87H from inlet of the channel. The tube center is located at X ¼ 6:87H, Y ¼ 5:625H.The winglets are thin triangular devices (shown on top right of Fig. 3) placed vertically on the fin surface, with their horizontal axis from the tip either angled outward or inward from the centerline. The position of the winglets is shown as W1 and W2. If it is angled outward (see W1 in Fig. 3), it is called common-flow down(CFD) configuration and if angled inwards (W2 in same figure), it is the common-flow-up (CFU) configuration. The axial distance (X11) between the leading edge of the first winglet pair in common-flow-down configuration and the channel inlet is 1.63H. The transverse distance (Y11) between the channel centerline and the leading edge of either winglet is 2.23H. The axial distance (X12) between the trailing edge of the either winglet and the channel inlet is 3.38H. The transverse distance (Y12) between the channel centerline and the trailing edge of either winglet is 3.69H. The other winglet of the first winglet pair is placed symmetrically about the channel centerline. The axial distance (X21) of the leading edge of second pair of winglets in common flow-up configuration from the inlet of channel is 3.96Hand transverse distance (Y21) from the centerline of the channel is 5.33H. The axial distance (X22) between trailing edge of the second pair of winglet and channel inlet is 5.71H and the distance (Y22) of it from the channel centerline is 3.88H. The length of all the winglets is 2.27H and their height is h ¼ 0:5H. Fig. 3.1 shows a layout of various configurations in which winglet pairs are mounted in the present study. Computations are performed for each of these configurations. Air has been considered as the working fluid, hence the Prandtl number is taken as 0.7. The winglets and oval tube are assumed to be at the temperature of the channel wall.

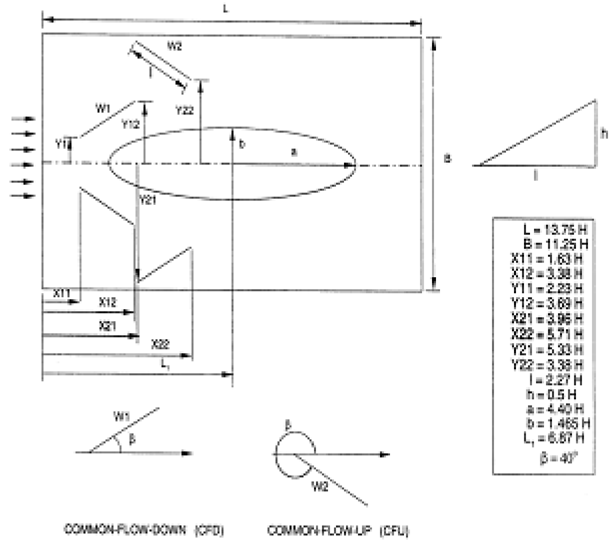

Figure 3.1: Two-dimensional representation of the computational domain

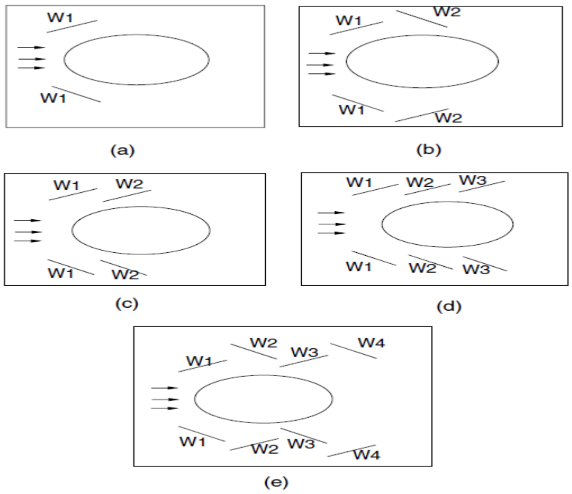

Figure 3.2: Various configurations of the winglet pairs. (a) Onewinglet pair (W1) in CFD. (b) Two winglet pairs (W1 in CFDand W2 in CFU). (c) Two winglet pairs (W1 and W2 both inCFD). (d) Three winglet pairs (W1, W2 and W3 in CFD). (e)Four winglet pairs (W1 and W3 in CFD; W2 and W4 in CFU)

3. Results and Discussions

The streamlines in the mid-plane of the channel of the study area for different inlet angle at *Re* = 7,000. The flow with inlet angle past the oval tube and it can be clearly found out that the wall in the direction of tube arrangement has periodic boundary condition which is plotted in Figure 5. It can be seenthat the flow is separated by the oval tubes and clearly exhibits the phenomenon of vortex near the rear ofthe tube. Meanwhile, the location of stationary point is shifted upward as well as the inlet angle decreases and the velocity gradient is also changed in the channel. Such behavior can be attributed to the periodical flow condition in vertical direction which results that the downstream flow is affected by upstream flow. Furthermore, it can be seen that the region of vortex enlarges obviously with the decrease of inlet angle. Besides, the sequence of pictures illustrates that the average flow velocity has been increased because of the enhancement of vortex.

4. Conclusions

In this project, a two-row heat exchanger unit model has been established and the inlet angle effects of plain fin-and-oval-tube heat exchanger have been investigated by FLUENT software. Some major conclusions are drawn as follows:

1) With the variation of inlet angle, the streamline has being changed remarkably. The layout of Vortex effected by inlet angle obviously and the hydrodynamics determine the distribution of the local Nusselt number.
2) The Nusselt number increases 16.7 % averagely at most for large *Re* comparing θ=30° with θ=90°. Meanwhile, the pressure drop increases about 57.8 % at the same time. Because of the excellent capability of heat transfer, the arrangement of θ=30° is frequently used for industrial applications as the pressure loss is acceptable.
3) The Nusselt number increases 18.5 % averagely at most for large *Re* comparing θ=25° with θ=90°. Meanwhile, the pressure drop increases about 62.9 % at the same time. Because of the excellent capability of heat transfer, the arrangement of θ=25° is frequently used for industrial applications as the pressure loss is acceptable.
4) Comparing the overall performance of different θ reflected by the ratio of j factor and f factor, the trend shows that 45° have an excellent performance. Meanwhile, the advantages are more obvious with the increase of *Re*.

A three-dimensional computational study of forced convection heat transfer has been accomplished to determine the flow structure and heat transfer in a rectangular channel with a built-in oval tube and delta winglet type vortex generators in various configurations. The duct was designed to simulate a passage, formed by two neighbouring fins in a fin–tube heat exchanger. The present study reveals that combinations of oval tube and the winglet pairs improve the heat transfer significantly, especially in the dead water zone. The mean span-averaged Nusselt number for the case of four winglet pairs, each two in sequence having a staggered configuration (Inner pair in common-flow-down and outer pair in common-flow-up arrangement) is about 100% higher as compared to no-winglet case at a Reynolds number of 1000. The enhancement in heat transfer, on the basis of finned oval tube as the base line case, is 43.86% for the case of two winglet pairs in staggered mode. A comparison of heat transfer for the cases of one, two and three winglet pairs (all in common-flow-down configuration) Confirms that the addition of each extra winglet pair causes further enhancement of heat transfer. The enhancement of heat transfer is marked even at far downstream locations. The winglets, at their moderate angle of attack, have quite streamlined like behaviour and so, are not expected to contribute much towards pressure losses. On the other hand, the contribution towards enhancement in heat transfer due to the winglet pairs is undoubtedly significant.

5. Scope for the Future

With the growing technology and demand for the heat transfer equipments this would be a fortune effect for the enhancement of heat transfer in the field of thermodynamics. This will be a beginning for the development of new materials for obtaining higher efficiencies in all the fields of science which are related to the transfer of energy. It is proved from the above project that the heat transfer enhancement is not only specified for some fields it also differentiates so many problems in the field of heat transfer.

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