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Additive Manufacturing and Novel Compact Heat Exchangers

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Heat Exchangers and their uses

Heat exchangers are used in many industries to transfer heat from one medium to another and can be used for both heating and cooling processes. The most common type is shell-and-tube heat exchangers but there are many others such as plate and frame. Some of their most common uses are in refrigerators, in air conditioning units, and to remove excess heat from electronics. Compact heat exchangers (CHEs) get their name from their large surface area to volume ratio. They can be made very small and "microchannel" CHEs have hydraulic diameters smaller than 1mm. Their size means they can be used for applications that other types of heat exchangers would not be suitable for, for example as heat sinks in electronics.

Optimising them can lead to significant size reductions and weight and cost savings as less material is needed to produce them; this is especially important when working with expensive materials.

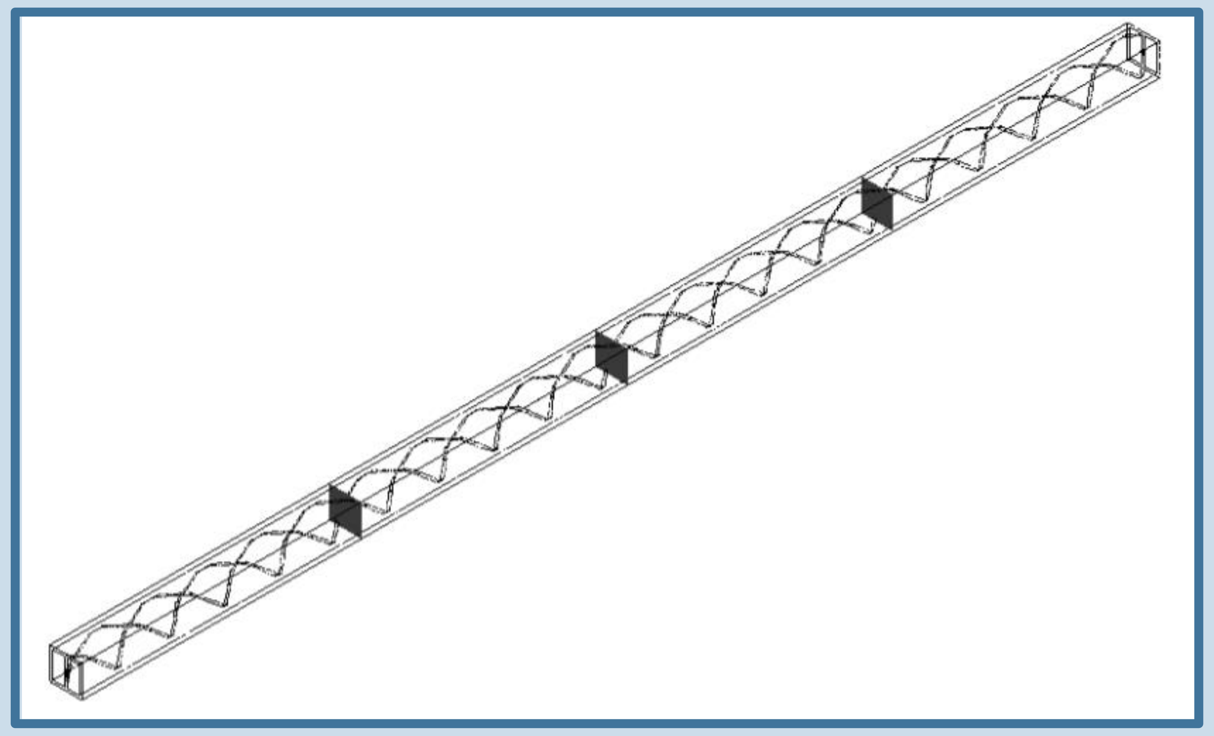
What is Additive Manufacturing?

Additive Manufacturing produces parts from three-dimensional computer-aided design (CAD) models by depositing material layer by layer in the required shape. It has become very popular in recent years, the most well-known type being 3D-Printing.

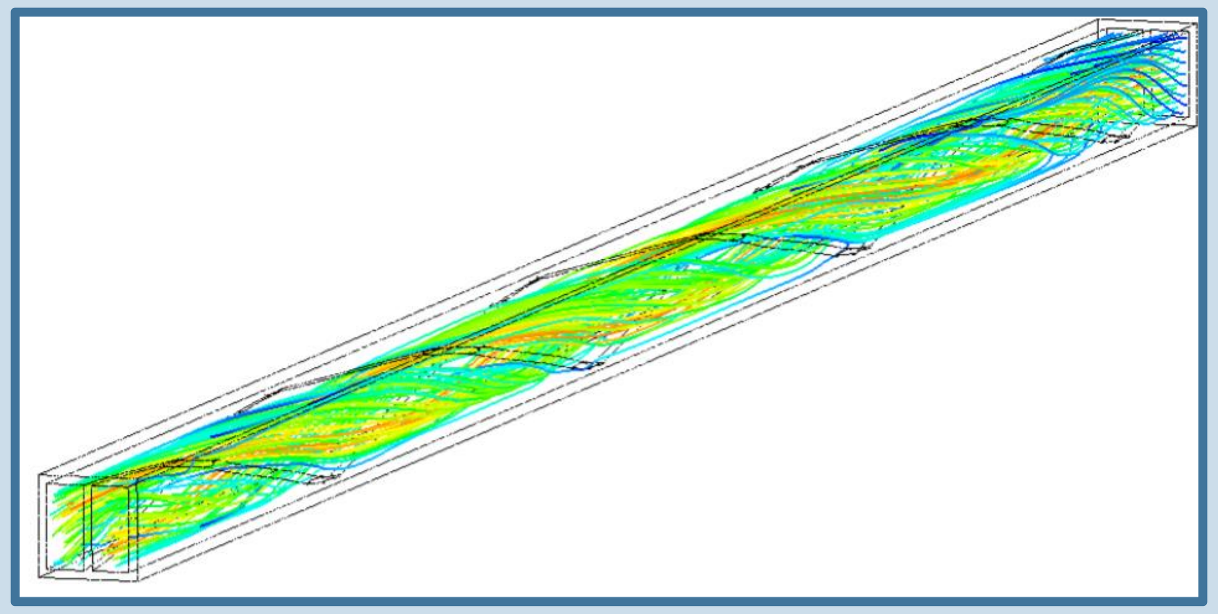
There are several methods within Additive Manufacturing for creating and joining these layers, which differ depending on the materials and machinery being used. The possible build materials can be plastic, metal, ceramics, glass, or composites which allows for almost any component to be created with this method. In the case of heat exchangers, the materials being used are metals. This involves a thin layer of fine metal powder being deposited across a build plate and selected areas of the powder being melted by a laser; this process is repeated until the build is complete.

Products with moving parts can also be printed such that the pieces are already assembled.

The manufacturing process has always been the limiting factor in the production of heat exchangers, but with the recent advancements in Additive Manufacturing, more complex designs of heat exchangers can now be considered, as designers now have complete creative freedom in the production process. As well as the benefits of geometrical freedom, the cost-effectiveness and time efficiency are improved in comparison to traditional methods because the cost of Additively Manufacturing a part does not rise with the complexity of the geometry and there is no assembly necessary as each device is printed as one part. These developments have created an exciting space for engineers to focus on the theory behind the optimisation, without the previous manufacturing limitations.



Square channel geometry with twisted tape insert (twist ratio 2.025) and location of three planes shown



Velocity streamlines along a square channel with twisted tape insert, twist ratio 10.125

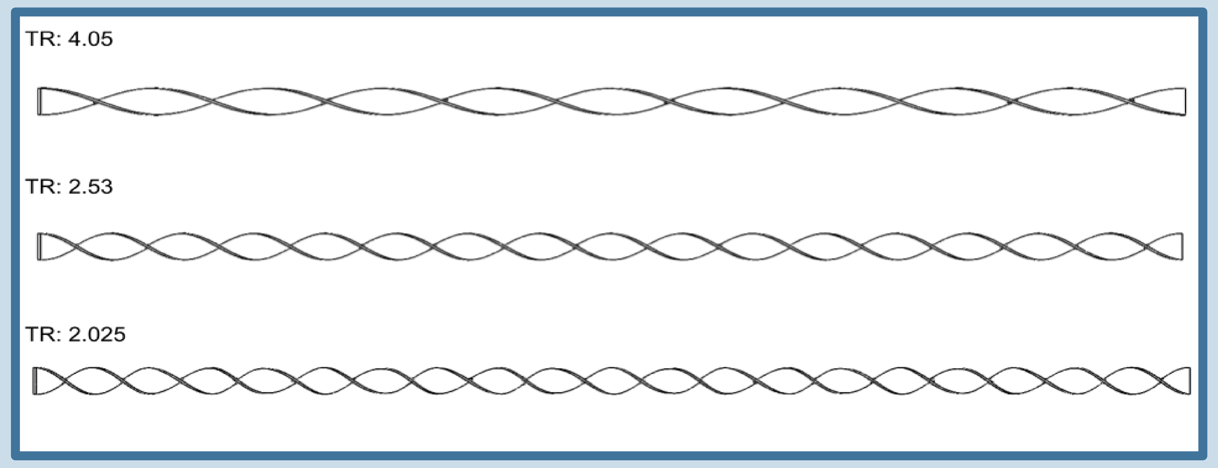
Project Goals

The objective in optimising heat exchangers is to increase heat transfer with as little pressure drop as possible. This is because the drop in pressure leads to more power being required to pump fluid through the heat exchanger to overcome this pressure drop and therefore the cost and energy required to run it increases. To increase heat transfer it is necessary to disrupt and thin the boundary layer and increase the heat transfer surface area. The flow in microchannel CHEs is predominantly laminar because their size restricts the development of turbulent flow[1], however turbulent flow is better for heat exchange because there is greater mixing and a thin sublayer. To promote turbulence, flow interruption can be achieved by creating artificial roughness, adding fins and dimples, varying geometrical parameters, or adding flow inserts. These features also increase the heat transfer surface area and since convection is the main heat transfer mode in heat exchangers, heat transfer is increased by increasing the surface area.

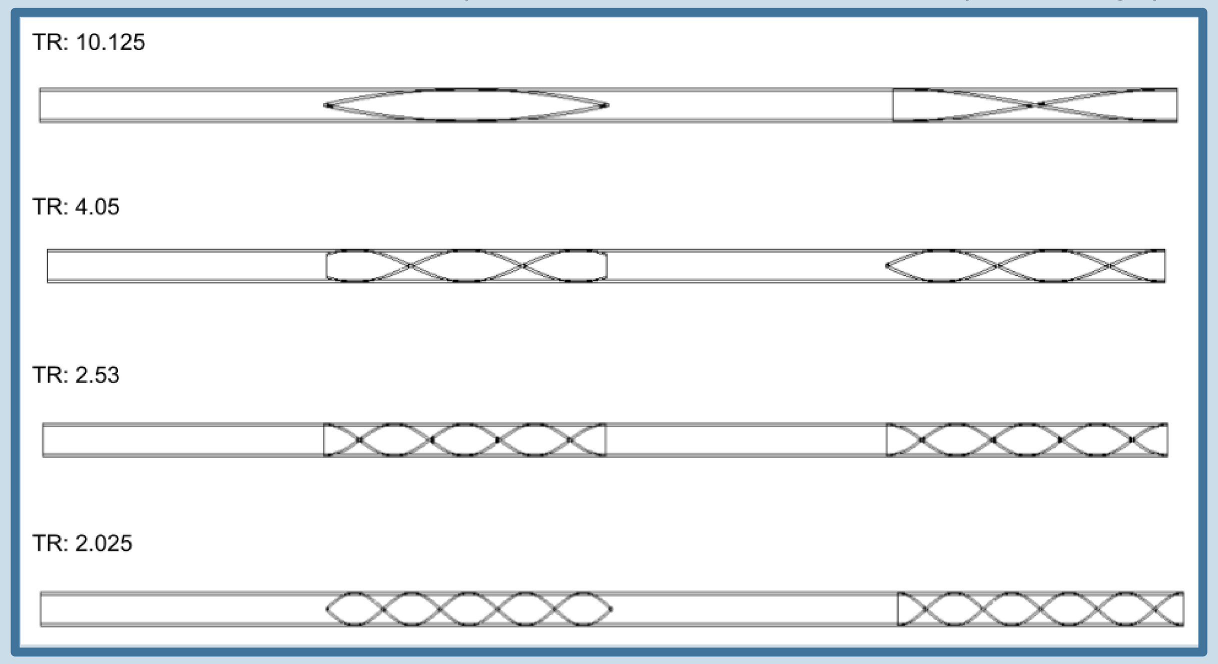
However, these extra features in the system increase resistance to the flow through friction and increase the flow path, which increases the pressure drop between the inlet and outlet of the heat exchanger and this is not desirable.

A performance factor, which incorporates the Nusselt number and friction factor, has been used to compare designs to a smooth channel.

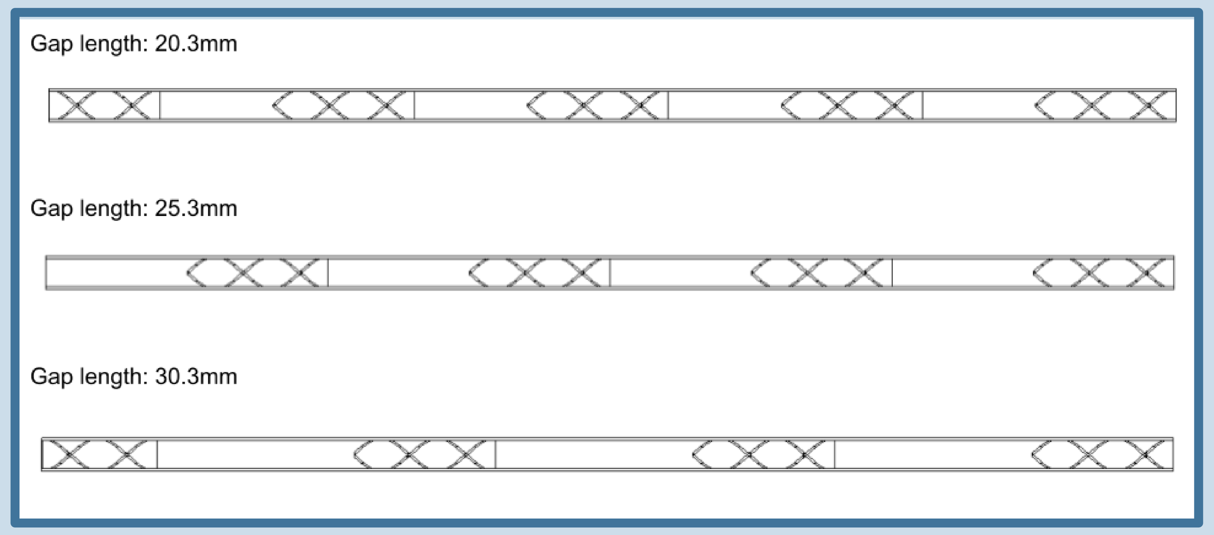
The solid used is Inconel-718 and the fluid is water.



Three of the twist ratios tested (a lower twist ratio means more twists per unit length)



Discontinuous twisted tape inserts of different twist ratios



Channels with different periods between discontinuous twisted tape inserts

Areas of Investigation

Initially, different Reynolds numbers were tested to see the effect of increasing Re on the performance factor. The first Figure shows the geometry used; a square channel with a simple twisted insert through the centre. The second Figure shows the velocity streamlines of the swirling flow caused by the twisted insert. This makes it easy to visualise how the flow mixing occurs and ensures that there is no region of fluid that doesn't come in contact with the heat transfer area.

Next, different twist ratios were tested, shown in the third Figure, where twist ratio is defined as the ratio of the linear length of 180° rotation of tape to the equivalent diameter of duct [2].

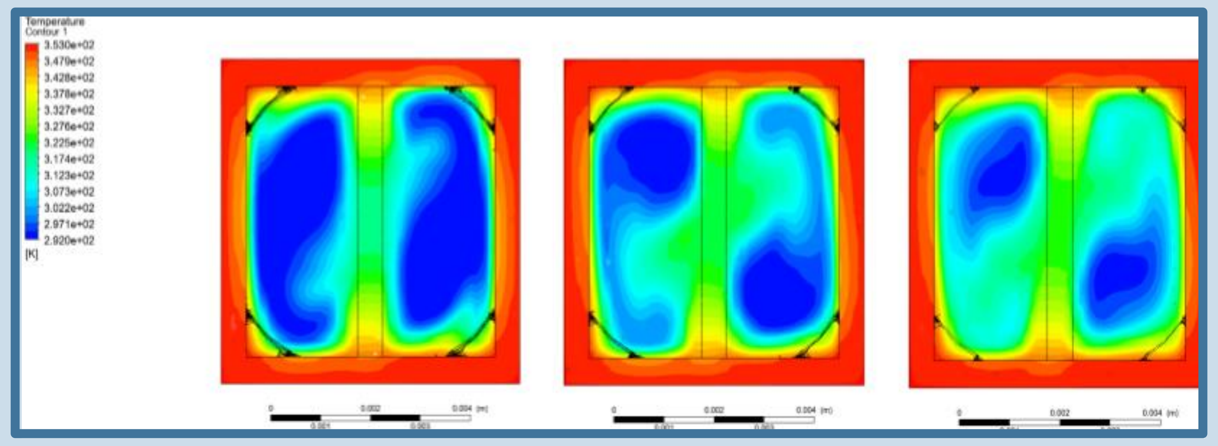
Then, the introduction of discontinuities was tested. The fourth Figure shows what is meant by discontinuous inserts. The sixth and seventh Figures show how the temperature contours along the channel vary with twist ratio. The contours are taken at the three planes shown in the first Figure. It is obvious that at the higher twist ratio the blue low-temperature region of fluid is dispersed much more quickly.

The period between twisted tape inserts was investigated next, the fifth Figure shows the various periods tested.

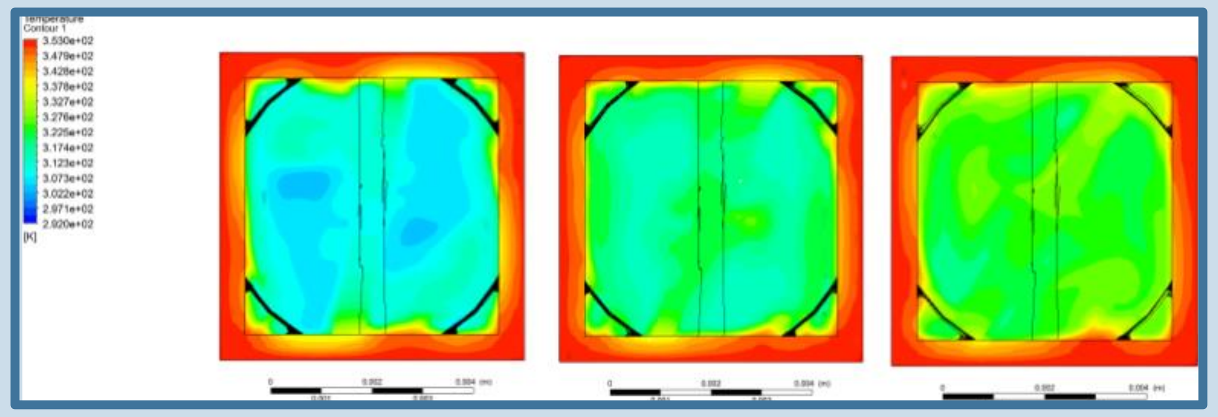
Once it was observed that the low thermal conductivity of the metal used wasn't allowing heat to be conducted to the centre of the twist, two solutions were proposed:

Different diameters of circular extruded cuts were taken through the centre of the geometry to remove the ineffective heat transfer area. The eighth Figure shows where the holes were extruded, and the different diameters considered.

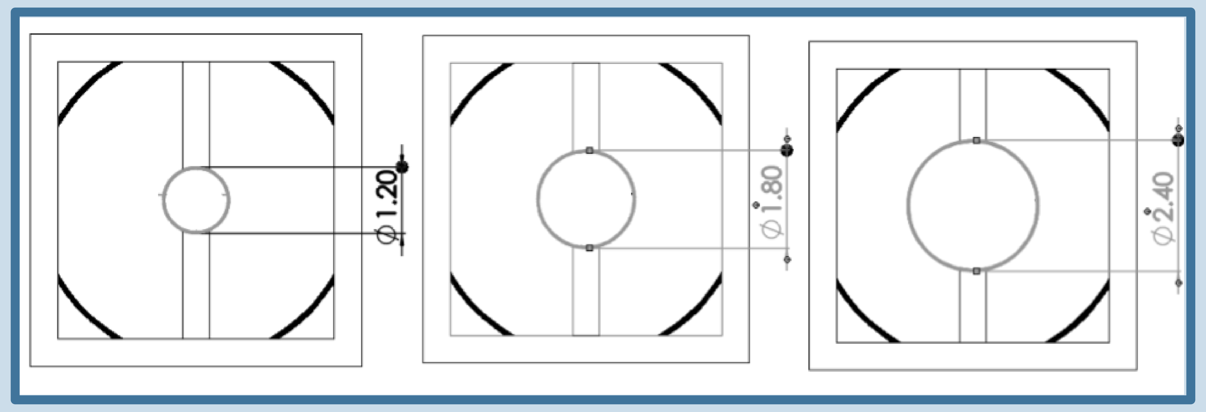
Alternatively, two more conductive metals, aluminium and copper, were tested with the same geometry. It can be seen in the last Figure that much more of the heat is conducted into the centre of the twist, so there is more effective use of the heat transfer area.



Temperature contours at three planes along the channel with twist ratio of 10.125



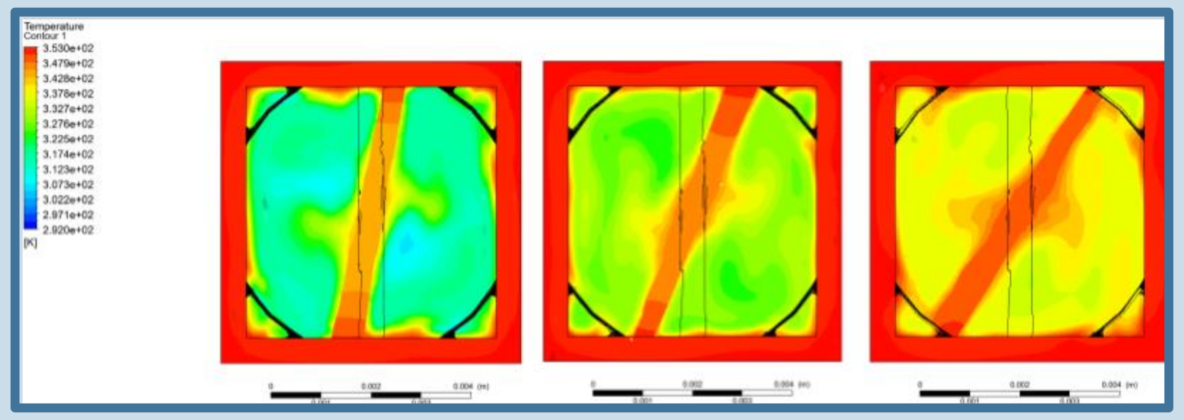
Temperature contours at three planes along the channel with twist ratio of 2.025



Three diameters of holes extruded through the centre of the twisted tape

Conclusions

- Increasing Reynolds number improved the performance factor because a larger Reynolds number signifies lower viscosity. This means a higher Reynolds number results in lower friction and an increase in flow rate, so the temperature gradient is kept high.
- There was an overall increase in performance factor with decreasing twist ratio. As twist ratio is decreased, the friction factor increases because the flow path is extended due to the radial motion of the flow. The Nusselt number also increases with decreasing twist ratio because the increased number of twists increases the swirl and fluid mixing.
- Introducing discontinuities decreases the friction factor because there is less obstruction to the flow and the length of the flow path is decreased. However, the Nusselt number also decreases because there is less mixing occurring in the smooth sections of the channel and the heat transfer area is decreased.
- There is a decrease in friction factor and Nusselt number with increasing period between inserts. Again, this is because the smooth section leads to less obstruction from inserts, but also less swirl and mixing, so increasing the length of this section increases the effect of these factors.
- The friction factor decreases with increasing hole diameter because increasing amounts of fluid are allowed to flow through the central hole. The trend in Nusselt number with hole diameter is not linear, too small a diameter and there is still too much ineffective heat transfer area, but at too large a diameter there is not enough mixing of flow to improve heat transfer. A performance improvement of 280% was found using the geometry with the medium-sized hole.
- Using more thermally conductive metals for the solid body of the heat exchanger improved the performance from a 250% improvement to a 300% improvement compared to a smooth channel. This is because the more conductive metal allowed heat to be conducted down through the twisted insert, therefore increasing the heat transfer surface area.



Temperature contours at three planes along copper channel with twist ratio of 2.025

References

[1] D.B. Tuckerman and R.F.W. Pease. "High-performance heat sinking for VLSI". In:IEEE ElectronDevice Letters2.5 (1981), pp. 126–129.DOI:10.1109/EDL.1981.25367
[2] Patil, S.V., Vijaybabu, P.V. Heat transfer enhancement through a square duct fitted with twistedtape inserts. Heat Mass Transfer 48, 1803–1811 (2012). https://doi.org/10.1007/s00231-012-1031-9