CONSTRUCTAL MULTI-SCALE CONVECTIVE STRUCTURES

by Tunde Bello-Ochende and Adrian Bejan

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This article illustrates the application of the constructal principle to the design of optimally shaped multi-scale convective structures. The design method is new and it accounts for the struggle for better global performance (objective, purpose) subject to global and local constraints.[1-6] In this article the global objective is the maximisation of the rate of heat transfer in a given space (volume, area, and so forth). The constraint is the fixed space (volume, area, materials, etc). The need to install more and more heat generation in a given volume has been the driving force behind many of the miniaturisation and unconventional ways of designing structures for heat and fluid flow.

In the old method of designing convective flow structures such as heat exchangers and electronics cooling, the designer starts with the channels and the duct. Flow channels and wall features (e.g. fins) are assumed. Later, these are connected and assembled into larger constructs that fill the space allocated to the device. The flows that are many and highly devise, are then forced to reside in the finite space that has been set aside for fluid flow and convection.

In constructal design, the flow architecture is the big unknown. The flow system is initially a black box endowed with objectives and constraints and, above all, with freedom to morph. The permanent struggle between objectives and constraints and, above all with freedom results in the product: the architecture (geometric form, shape and structure) that performs optimally or close to the optimal design. One class of heat and fluid structures that have been optimised are the configurations in which optimal spacing exists [6-10]: stacks of parallel plates, staggered plates, cylinders in cross-flow, and pin fin arrays with impinging flow. In the above examples there is one important characteristic that links all the optimised configurations: the optimal spacing is a single length scale that is distributed uniformly throughout the given volume.

In constructal theory the single spacing philosophy is replaced by the search for optimised flow structures with more than one free length scale. Three examples of works done by the authors using the principle of constructal design applied to multi-scale convective structures are outlined below.

Fitting the duct to the 'body' of convective flow:
In this work the authors considered the problem of cooling a heat-generating line (or a narrow strip) with a stream that flows parallel to the strip.[2] The global objective was to fit this convective flow into the smallest volume or to pack the largest heat transfer rate into a volume of fixed size and variable shapes. Two sets of results were presented: heat-generating strip cooled inside a duct of rectangular cross-section, and a tube with isothermal internal surface. In both cases the volume was fixed, and then we determined the best geometry (structure) that will pack the maximum heat transfer rate.

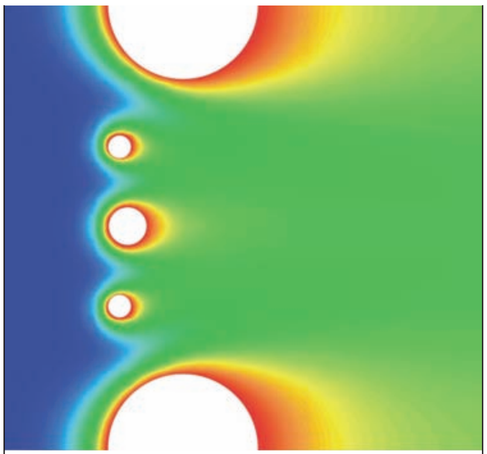
Maximal heat transfer density:
Plates with multiple lengths in forced convection. The fundamental problem of cooling a flow structure with several length scales was studied by simulating the flow and heat transfer for a wide variety of flow configurations. Each simulation shows that the entrance region of every parallel plate channel has a core of unused (isothermal) fluid. In this wedge-shape region we inserted progressively smaller heat generating plates, and optimised the multi-scale assembly.[3] This was done progressively until diminishing returns set in. The number of new plate inserts stopped at two, as further increases in the number of length scales do not significantly affect the performance of the flow assembly. This method can be used to develop multi-scale non-uniform structures for heat exchangers and cooled electronics.

Multi-scale cylinders in cross-flow:
In this work we extend the idea and concept of the work above to multi-scale cylinders in cross-flow.[4] The multi-length scales are the diameter and the spacing between the cylinders. The largest cylinder defines the overall extent of the flow space. This work reports the optimised flow architectures and performance for structures with one, two and three cylinder sizes, which correspond to structures with one, two and four degrees of freedom. The non-uniform distribution of these length scales means that progressively smaller cylinders are placed near the entrance region of the assembly, i.e. in flow region inhabited by fluid that has not contributed to the global heat transfer enterprise. A sample plot for temperature field for cylinders in cross-flow (three cylinder sizes) is shown

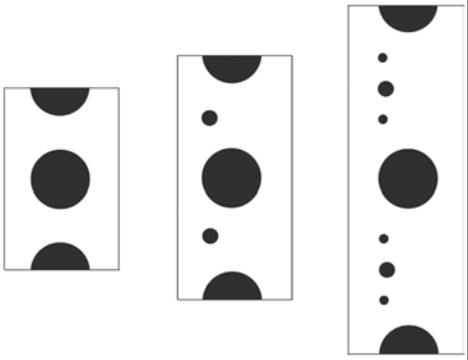
below. This is a scale drawing of the optimised flow architectures with one, two and four free varying length scales. Reading from left to right, the figure shows how the optimised spacing between cylinders increases when new cylinders (with optimised diameters) are placed in the existing gaps.

Conclusion

According to constructal theory, a convective flow structure that has objectives and is optimised under global constraints, morphs to produce shape and structure. The constructal law states that, in time, flow structures morph in the direction of better (easier) flowing structures. The generated architecture is robust and performs optimally or close to the optimal design.



→ *1. Simulated temperature field for multi-scale cylinders in Cross-Flow arranged in a row. (Red colours depict high temperature, and dark blue depicts low temperature).*



→ *2. Effect of increasing complexity and pressure drop number on optimised multi-scale structure.*

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