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Custom-designed 3D-printed metallic fluid guiding elements for enhanced heat transfer at low pressure drop

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ABSTRACT

3D-printed inserts allowing for the tailored guiding of a fluid flow for enhanced heat transfer at low pressure drop are presented. The fluid guiding elements (FGE) introduced in this contribution are based on B-spline surfaces allowing for a dedicated subdivision of the flow in several partial flows which are alternatingly contacted with the heat transferring wall, thereby maintaining a high local heat transfer all along the wall which leads to an enhanced overall heat transfer capacity. By changing the design parameters, the number of partial flows and the individual residence time at the wall can be adjusted to the needs of the considered application. Besides the discussion of the basic design strategy, the concept proposed is validated *via* simulation and experimental studies. Using the technique of selective laser melting, the produced metallic FGE exhibit walls of only 150 μm thickness thereby imposing only a marginal obstruction of the flow. It is shown that by the use of the FGE the length of a pipe-in-pipe heat exchanger can be drastically reduced.

1. Introduction

In all fields of process engineering, the (internal) design of the devices for the different unit operations predetermines the performance of the overall process in terms of efficiency (*e.g.* heat exchangers) and product quality (*e.g.* chemical reactor). Hence, internals for chemical reactors, mixers and pipe-in-pipe heat exchangers to name but a few are widely used to intensify the accordant processes. Keeping to the example of heat exchangers, the introduction of swirl or turbulence to the fluid flow is widely discussed in literature. Besides active methods like the imposition of an oscillation to the fluid flow [1], especially passive methods are investigated in literature: Next to the use of static mixers [2], or corrugation of the tubes [3] and the addition of nanoparticles to the fluid [4,5] for introduction of swirl and the enhancement of the fluid's net thermal conductivity, respectively, tube inserts are most often proposed and demonstrated in experiment and/or numerical simulation. The inserts evaluated range from helical structures [4,6,7], propellers and twisted tapes [8–11] over fins and comparable inserts [1,12–15] to solid foams and other porous materials [16,17]. A comprehensive review on different passive methods for enhancement of the heat transfer performance of pipe-in-pipe heat exchangers is given by Liu and Sakr and by Omidi et al. in Refs. [18,19]. It is worth highlighting, that the considerations for the heat exchangers described above also hold for chemical reactors for which the effective removal/introduction of heat is often mandatory for a safe, reliable and efficient process. Likewise, inserts in packed bed reactors as well as structured catalyst support materials are discussed in order to reach these objectives [20–22]. Though, due to manufacturing costs or even lack of feasibility there have always been limits of imagination for the design of such inserts.

Nowadays, additive manufacturing – with 3D printing of metals *via* selective melting of metal powder using an electron (SEBM [23]) or laser beam (SLM [14,22,24,25]) in particular – allows for the production of very special geometrical structures impossible to achieve using conventional material processing technologies or at least not achievable at reasonable costs [26]. This revolution in material processing opens up completely new degrees of freedom for the design of components. Especially in combination with computational tools like CFD, tremendous potential for process intensification can be ascribed to thin-walled, 3D printed inserts guiding a fluid flow in, *e.g.*, heat-intensive unit operations such as heat exchangers or chemical reactors.

Here, we present the concept of fluid flow guiding elements (FGEs) produced by selective laser melting (SLM) which, based on freeform surfaces (B-splines), are not aiming for generating turbulence but rather for guiding the fluid flow along desired flow paths. By adjusting well-defined geometrical parameters, the fluid flow paths and, as a result,

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Nomenclature

Symbols

η_{th}	Thermal effectiveness factor
E/J	Energy
h/J	Sensible enthalpy
n/-	Number
$\dot{m}$/kg h^{-1}	Mass flow rate
p/Pa	Pressure
P/W	Power
$\dot{Q}$/W	Heat flux
T/K, °C	Temperature
S_{h}/J	Heat
t/s	Time
v/m s^{-1}	Flow velocity
ε/-	Void fraction
λ/W m^{-1} K^{-1}	Therm. conductivity
ρ/kg m^{-3}	Density
$\vec{g}$	Gravity vector
$\vec{J}$	Diffusional flux
$\overline{\overline{\tau}}$	Tension tensor
$\vec{v}$	Velocity vector

Indices

ag	Annular gap
in	Inlet position
it	Inner tube
j	Designator of pf
out	Outlet position
pf	Partial flow
p-y	Parallel in y-direction
p-r	Parallel in radial direction
ref	Reference
rep	Repetition
s	In series

Abbreviations

FGU	Fluid guiding unit
FGE	Fluid guiding element
SLM	Selective laser melting

the temperature and concentration profiles can be "programmed" following the needs of a given application. Exemplarily, in this contribution we demonstrate the basic concept using a pipe-in-pipe heat exchanger equipped with FGE internals and compare the experimental data with results from CFD simulations.

2. Rational design of the FGEs

2.1. General design targets

The design of FGEs for heat transfer applications such as heat-exchangers or chemical reactors from scratch focuses on the general targets listed below (see also Fig. 1). At first glance these targets partly stand in contradiction to each other, but they can all be fulfilled by the systems presented in this contribution:

(1) Guidance: Based on fundamental theory of heat transfer, the temperature gradient within the "boundary layer" of a fluid flowing along a heat transferring wall predetermines the heat flux from/to the wall. For a fluid being heated/cooled at a heat transferring wall, this gradient – and thereby the heat flux – decreases upon heating/cooling along the wall. Here, turbulent flow characteristics can help maintaining high gradients by velocity vectors non-parallel to the wall. This is actually the main argument for the measures described in the introduction although literally at the expense of an additional pressure drop. Therefore, it is the aim of the FGEs under study here to generate a large temperature gradient at the wall with minimal additional pressure drop. This can be achieved by subdivision of the fluid flow in several partial flows and their smart guidance by the FGEs: By allowing only a short – but well defined – contact time/distance of each partial flow at the heat transferring wall, the penetration depth of the heat is small and, thus, during that time/distance the temperature gradient (*viz.* heat flux) is large. After a defined period of time/distance the partial flow is guided away from the wall to a region where equilibration takes place. At the same time, a second (third, fourth,…), equilibrated partial flow is guided to the wall replacing the first one. By this alternating contact of the heat transferring wall with thermally equilibrated partial flows, which effectively corresponds to an extension of the thermal lead-in area to the whole length of the wall, an optimized (*viz.* large) temperature gradient within the "boundary layer" can be maintained all along the heat transferring wall.

(2) Obstruction: The resistance which the inserts impose on the fluid flow should be small in order to minimize the generation of changes in the local velocity vectors and, thus, to minimize the additional pressure drop. At the same time the FGEs should guide the fluid flow as mentioned in (1). As a result, the FGEs should be composed of smoothly bent surfaces with thin walls. Moreover, the surface area of the FGEs per volume should be as small as possible in order to minimize the additional pressure drop due to wall friction except for applications, which explicitly call for a high surface area per volume for other reasons, *e.g.*, utilization of the FGEs as a catalyst support in a structured reactor.

(3) Manufacturing: The elements should preferably be applicable as tube inserts (*e.g.*, in a pipe-in-pipe arrangement) in order to support low fabrication cost. Certainly, the FGE should be produced at low cost but still exhibit a complex geometry necessitated by the requirements listed above. Thus, additive manufacturing methods are

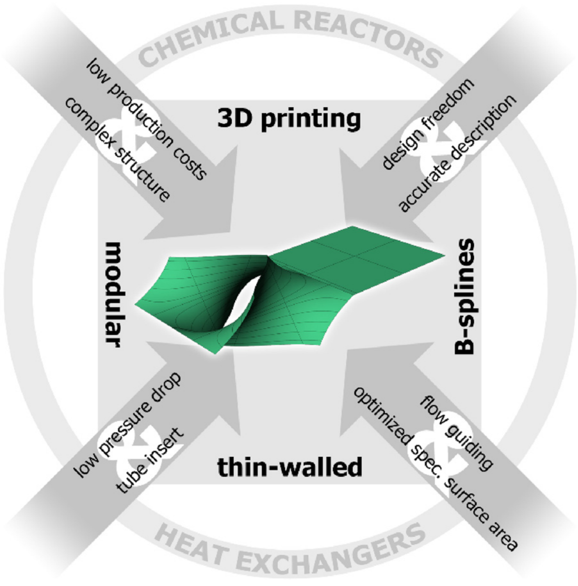

Fig. 1. Criteria considered for the FGE-design.