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Swirl flow tube reactor technology: An experimental and computational fluid dynamics study

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HIGHLIGHTS

- A novel reactor technology has been evaluated experimentally and computationally.
- Novel reactor shows an increase in heat transfer and pressure drop.
- CFD model allows to explain higher heat transfer and pressure drop.
- Results confirm the potential of the SFT technology in steam cracking furnaces.

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ABSTRACT

A novel reactor technology for steam cracking reactors, called Swirl Flow Tube (SFT), has been evaluated experimentally and computationally. A comprehensive experimental dataset has been acquired on a newly built test set-up covering a wide range of Re numbers (30,000–120,000) and different swirl flow tube designs. The swirl flow tubes result in an increase of heat transfer by a factor of 1.2–1.5 compared to a straight tube. The increased heat transfer is accompanied by an increased pressure drop by a factor 1.4–2.2 compared to a straight tube depending on Reynolds number and geometry. A computational fluid dynamics model was adopted that is able to capture the main flow properties of the swirl flow tube and this model allows to attribute the increased heat transfer and pressure drop to a higher wall shear stress. The experimental and simulation results confirm the great potential for the application of the SFT technology in steam cracking furnaces because of the lower average wall temperatures and the resulting reduction of coke formation in the reactor coil.

1. Introduction

Steam cracking of hydrocarbons is the main industrial process for the production of almost all important base chemicals [1,2]. In this process classically tubular reactors suspended in large gas fired furnaces are adopted. Two side reactions detrimentally influence the process operation and profit margins, i.e. CO formation and coke deposition on the inner surface of the cracking coils and in the transfer line heat exchangers [3–5]. Accumulation of coke on the reactor wall on the one hand reduces the open cross-section of the tubes, resulting in an increased pressure drop over the reactor coil. On the other hand the coke layer inhibits heat transfer from the tube to the process gas, and hence is responsible for the rising tube wall temperatures [6]. If the reactor pressure drop is too high or the external tube skin temperature exceeds the metallurgical allowable temperature, operation is halted and the coke is burned off with a steam/air mixture. On the mechanical side, carburization can lead to deterioration and/or damage to the tube material. In short, coke formation affects the steam cracker's economics in 3 ways: increased energy consumption, loss of furnace availability because of decoking/mechanical failure and a decrease in olefin selectivity due to an increased pressure drop [7].

A lot of effort has been spent in the past 30 years to find appropriate methods to suppress coke formation [3,8–17]. These technologies can be roughly divided in three categories: the use of additives [13,14,5], metal surface technologies [18,19] and the use of mechanical devices for enhanced heat transfer [20–24]. In the last category three-dimensional reactor designs are used to enhance heat transfer [20], resulting in lower wall temperatures and coking rates. Designs can be divided in two classes based on the physical reason of increased heat transfer, i.e. increased internal surface area or enhanced mixing. Examples of designs belonging to this first class are finned tubes, which have been intensively studied and have been installed industrially [20,21]. As shown in Brown [24] the ratio of heat transfer improvement of a straight finned tube is linearly dependent on the surface

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Nomenclature

Roman

A	amplitude of helicoidal centerline of swirl flow tube (m)
CFD	computational fluid dynamics (–)
c_p	heat capacity at constant pressure (J/kg/K)
d_{in}	tube internal diameter (m)
E	total energy per unit mass (J/kg)
f_f	Fanning friction factor (–)
I	turbulence intensity (%)
IHT	Intensified Heat Transfer Technology (–)
k	turbulent kinetic energy (m^2/s^2)
l	turbulence length scale (m)
L	axial length of a tube (m)
LMTD	log mean temperature difference (–)
MERT	mixing element radial tube (–)
Nu	Nusselt number $\frac{Ud_{in}}{\lambda}$
p	pressure (Pa)
P	pitch of helicoidal centerline of swirl flow tube (m)
Pr	Prandtl number $\frac{c_p\mu}{\lambda}$
Q	heat flux (W)
QUICK	quadratic upstream interpolation for convective kinetics (–)
RANS	Reynolds-averaged Navier–Stokes equations (–)
Re	Reynolds number (–)
RSM	Reynolds Stress Model (–)
SFT	Swirl Flow Tube (–)
SIMPLE	semi-implicit method for pressure-linked equations (–)
T	temperature (K)
U	heat transfer coefficient ($W/m^2/K$)
v	velocity (m/s)
y	cell distance from wall (m)

Greek

α	surface roughness correction factor (–)
ε	turbulent dissipation rate (m^2/s^3)
λ	thermal conductivity (W/m/K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
φ	mass flow rate (kg/s)
Ω	tube cross-sectional surface area (m^2)

Subscripts

in	at tube inlet
m	mass
p	constant pressure
out	at tube outlet
h	heated
t	turbulent
avg	mixing cup

increase. This work focusses on the second class of reactor designs, that achieves enhanced heat transfer by increasing mixing of the process gas.

Enhanced mixing leads to a more effective and homogeneous heating of the process gas. As shown from two-dimensional [25] and three-dimensional simulations [20][26] large radial concentration and temperature gradients exist in industrial crackers and better mixing could reduce these gradients leading to lower coking rates. Moreover, the more uniform radial temperature profile limits under- and over- cracking. One of the most applied examples is the Mixing Element Radiant Tube (MERT) patented by Kubota [22] and claiming an increase of the heat transfer coefficient by 20–50% compared to a straight tube [22]. This increase is explained by increased fluid mixing and break down of the thermal boundary layer on the tube internal surface by the mixing element. Progressively, the design of this element has been optimized to reduce pressure drop, first through the use of the SLIT-MERT product and the latest design X-MERT. For an increase of heat transfer by a factor of 1.4 (compared to a straight tube) the increase in pressure drop is reduced from 3.0 for the MERT to 2.4 and 2.1 for the Slit-MERT and X-MERT respectively.

An second approach has been developed by the Lummus Technology division in cooperation with Sinopec. Their Intensified Heat Transfer Technology (IHT) is based on the use of radiant coil inserts at certain locations in the tube [23]. The coil inserts have a twisted (100–360°) baffle integrated within inner surface and have the same diameter and metallurgy as the radiant coil. By strategic placement, these inserts create turbulence in the process fluid, thus reducing the boundary layer and improving mixing and heat transfer while limiting the added pressure drop as much as possible. The pressure drop was increased by a factor of 1.15–1.20 compared to a straight tube. A CFD analysis confirmed the beneficial effect on the heat transfer and uniformity of the temperature profile while only simulating a friction increase of 15%. The helicoidal effect of the insert on the flow tends to fade away with distance, allowing careful evaluation of the optimum locations for the inserts. A distance equal to 10–15 times the reactor inner diameter

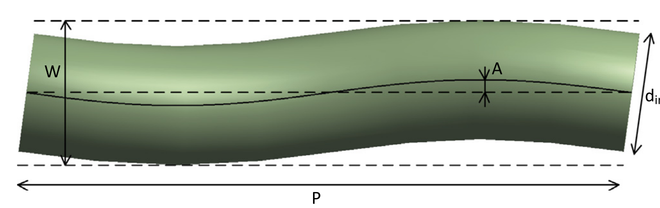

Fig. 1. Schematic drawing of one helicoidal turn of a swirl flow tube (*A*: helix amplitude; *P*: helix pitch; d_{in}: tube inner diameter; *W*: tube width).

proved to be a good tradeoff between swirl flow intensity and pressure loss.

Recently a new steam cracking reactor technology has been patented, the so-called Swirl Flow Tube (SFT) technology, aimed at enhanced mixing [27]. In this case the cross section of the tube remains circular but the centerline follows a "small amplitude" helicoidal path providing enhanced mixing. The term "small amplitude" refers to the amplitude of the helicoidal path being equal to or smaller than the radius of the tube, and hence leaving a line of sight through the tube. Fig. 1 shows one helicoidal turn of a swirl flow tube characterized by the helix pitch P and the helix amplitude A. The relative amplitude and relative pitch are defined with respect to the tube inner diameter. At each position in the tube, the cross sectional area is perpendicular to the helicoidal centerline. Hence the tube does not have the shape of a set of stapled coins but truly is a bended tube. This technology finds its origin in biological fluid mechanics where it is seen that helicoidal stents reduce stagnation zones compared to clinical arterial bypass grafts. This led to less instances of intimal hyperplasia which is promoted by regions with low wall shear [28]. Although the flow regime in biological fluid mechanics is laminar in contrast to the highly turbulent flow regime in pyrolysis reactors, the potential advantage of these tubes for pyrolysis reactors is the high degree of swirl flow that is induced. This can be described as a rotation of the flow about the main axis of the pipe, which in this case is helicoidal