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CFD modeling of homogenizer valve: A comparative study

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ABSTRACT

Designing an efficient homogenizer valve requires an in-depth understanding of the flow structure in the valve region. Therefore, the choice of an appropriate strategy in the numerical simulation of homogenization and chemical process plays a significant role and determines the accuracy of results which returns an improved design criterion. The performance of two computational fluid dynamics (CFD) strategies in the simulation of a homogenizer valve is assessed in this study; namely, the large eddy simulation (LES) and hybrid LES-RANS methods. For LES calculations, two sub-grid scale (SGS) models are considered: (a) RAST one-equation model (OEM) (b) dynamic Smagorinsky model (DSM) while the SST-SAS and delayed detached eddy simulation (DDES) methods are the variants of a hybrid-type RANS-LES approach. The predictions of these models are compared with the experimental data available in the literature. The comparisons show that an LES can reproduce accurate information in terms of main parameters such as the mean velocity and turbulent kinetic energy that are important in designing the homogenization process. However, the SST-SAS predictions are not as accurate as the DDES and LES ones, especially downstream of the gap in reproducing the mean velocity and turbulent fluctuations.

1. Introduction

Homogenization is a mechanism which is responsible for the subdivision of particles into very small sizes to create an emulsion for further processing. Food and dairy industries benefit from this process to a greater extent because the homogenization has a significant role in improving the product quality and taste. In this process, the flow passes through a very narrow gap or tube, experiencing a high pressure and turbulent structure. Then this “squeezed” flow is injected to a chamber causing the dispersion of particles due to the sudden change in the velocity gradient. Therefore, a clear understanding of the flow structure inside the valve provides a vital information in designing and optimizing homogenization devices in terms of energy efficiency and performance.

Computational fluid dynamics (CFD) is one of the principal strategies in the numerical investigation of engineering fluid flow associated with chemical engineering. This approach provides a detailed insight into the turbulent structures with main parameters such as the velocity, pressure and turbulent kinetic energy. Two of the earliest studies are conducted by Kleinig and Middelberg (Kleinig and Middelberg, 1997), and Stevenson and Chen (Stevenson and Chen, 1997). They studied the flow field inside the homogenizer valve with the k-ϵ models in collaboration with the Reynolds-averaged-Navier–Stokes (RANS) equations and found satisfactory results. There are a few studies, applying CFD for the homogenizer valve in the literature. The majority of these studies focused on a two-dimensional model of the flow in homogenizer valves with various versions of k-ϵ models (Miller et al., 2002; Casoli

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Nomenclature

C_μ	eddy–viscosity coefficient
$\bar{C}_s$	Smagorinsky coefficient
G	filter function
F_1	blending function
g	gravitational acceleration
h	gap height
k	total turbulent kinetic energy
L_{ij}	Leonard stress
P	production term
Re	Reynolds number
$\bar{S}_{ij}$	mean strain–rate tensor
$\bar{u}_i$	grid–filter velocities
$\tilde{\bar{u}}_i$	test–filter velocities
$\bar{W}_{ij}$	mean vorticity tensor
y^+	dimensionless wall distance $(\bar{u}_\tau y/\nu)$
δ	boundary layer thickness
$\delta_{i,j}$	Kronecker's delta
Δt	time step
$\bar{\Delta}$	grid–filter width
$\tilde{\Delta}$	test–filter width
ν, ν_T	laminar and turbulent viscosities
ρ	density
$\tau_{i,j}$	sub–grid scale stress tensor

Abbreviations

DDES	delayed detached eddy simulation
DSM	dynamic Smagorinsky model
LES	large eddy simulation
RANS	Reynolds averaged Navier–Stokes
RAST	Rahman–Agarwal–Siikonen–Taghinia
SAS	scale-adaptive simulation
SGS	sub-grid scale
SST	shear stress transport

Subscript

i, j	variable numbers

et al., 2010; Floury et al., 2004; Kelly and Muske, 2004; Köhler et al., 2007; Steiner et al., 2006; Raikar et al., 2009). Håkansson et al. (Håkansson et al., 2012) performed numerical studies based on the standard, RNG and realizable k-ϵ models for a three-dimensional homogenizer valve. They reported that the standard k-ϵ model is incapable of predicting the flow field accurately, especially close to the gap exit. They also noticed that all the applied turbulence models failed to reproduce the correct level of turbulent kinetic energy at the gap entrance.

According to the above-mentioned studies, the main understanding of flow structure in homogenizer valves are based on RANS approaches, exhibiting a general information on the flow inside the valve with the time-averaging scheme. The "steady-state" RANS cannot reflect a detailed picture of instantaneous velocities or fluctuations that vanish due to the averaging process.

With developing computational power, the large eddy simulation (LES) has become a suitable and powerful approach in the modeling of flow with a rapid transient nature. Although, an LES requires higher computational cost and grid resolution than those of an RANS, its ability to capture the flow structures at a wide range of turbulent scales makes it a promising alternative approach compared to an RANS in simulating complex flows. The application of LES has attracted an increasing interest in the industrial design and modeling. The studies based on the LES in analyzing the flow field in valves are so scarce and there are almost no reported researches concerning the LES-based simulation of the flow field in homogenizer valves.

An LES decomposes the flow structures to the large and sub-grid scale (SGS). The larger eddies are solved directly while the SGS part is modeled. The criterion for this decomposition of scales is usually based on the grid size, serving as a filter. The main difference among various LES approaches is in the applied SGS model, determining the mechanism in reproducing small scales based on various methods. Two of the most common SGS models are the Smagorisnky model (SM) (Smagorinsky, 1963) and the dynamic Smagorinsky model (DSM) devised by Germano et al. (Germano et al., 1991). The main difference between these two models lies within the procedure of determining the eddy viscosity coefficient. The DSM computes the eddy-viscosity coefficient locally varying in time and space while the SM utilizes a constant eddy-viscosity coefficient which is not suitable for complex flows (Olsson and Fuchs, 1996). On the other hand, the DSM filtering process relies on two filters, namely grid and test filters, causing a negative eddy-viscosity locally that makes it not as robust as the SM. Recently, Taghinia et al. (Taghinia et al., 2015) have developed a one-equation version of the RAST (Rahman–Agarwal–Siikonen–Taghinia) SGS model with a variable eddy-viscosity coefficient, responding to both the strain-rate and rotation-rate parameters, and therefore it is sensitive toward flow separation and reattachment. This model utilizes a single filter (unlike the DSM) making it more robust in computations. These features make this model capable of simulating complex flows where the effects of sudden pressure drop, high strain-rate and streamline curvature prevail.

In order to overcome the high computational demand of an LES, the hybrid LES-RANS method such as the SST-SAS is devised in which both the RANS and LES are applied according to the location of solid boundaries. The SST-SAS (Scale-Adaptive Simulation) turbulence model belongs to the category of a hybrid-type LES-RANS model developed by Menter and Egorov (Menter and Egorov, 2010); the RANS-SST k-ω is applied close to the wall region and the LES in the rest of the domain. According to the authors' knowledge, there is no reported performance of the SST-SAS in the simulation of fluid flow in valves. The detached eddy simulation (DES) or its improved version like delayed detached eddy simulation (DDES) can also be regarded as an hybrid method. However, unlike the SST-SAS, the DES is influenced by the grid spacing (which will be discussed in the next section). The RANS part of DES can be an RANS turbulence model such as the Spalart-Allmaras (Spalart and Allmaras, 1994) model or the realizable k-ϵ model.

This paper aims at investigating the flow structures in the homogenizer valve using four turbulence models. Two of them are one-equation RAST and dynamic Smagorinsky models which belong to the LES approach; the other two are SST-SAS and DDES that are variants of an hybrid method. Since there are no studies based on these approaches in the literature and therefore the current study provides a suitable benchmark to assess the ability of these models in predicting the real behavior of fluid flow especially around the gap area. The predictions are compared with the experimental data available in the literature(Håkansson et al., 2012; Innings and Trägårdh, 2007).