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CFD simulation of solid–liquid flow in a two impinging streams cyclone reactor: Prediction of mean residence time and holdup of solid particles

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ABSTRACT

The hydrodynamic behavior of a two impinging streams cyclone reactor (TISCR) was simulated using the computational fluid dynamics (CFD) technique. An Eulerian multiphase model has been used to compute the unsteady flow of a solid–liquid suspension in a 3D geometric configuration. The mean residence time (t_m) and holdup of solid particles were calculated from a number of simulated results obtained at different solid and liquid flow rates. The CFD simulation results were compared with the experimental data available in the literature and a fairly well agreement was observed. Such a correlation was gradually improved with increasing solid flow rate.

1. Introduction

Impinging stream contactors, being a relatively novel device for process intensification was first proposed and investigated extensively in the USSR by Elperin [1] during 1960s. It is arguably one of the more effective methods for intensifying the rates of mass and heat transfer in several diverse chemical engineering processes. In a typical impinging stream device, two feed streams, flowing either parallel or counter-currently to each other, collide to form a highly turbulent and high shear impingement zone. Each stream may consist of two immiscible phases, e.g., solid–liquid, solid–gas and gas–liquid. Such impinging streams create the following effects which in turn promote the heat and mass transfer rates in particulate systems:

1. Increase in relative velocities between the phases.
2. Increase in the residence time of particles due to oscillatory motion within the impingement zone.
3. Enhancement of the effective area for mass and heat transfer which could be nearly identical to the total surface of the particles in the flow.
4. Potential for excellent mixing within the impingement region which in turn enhances the overall mass and heat transfer rates [2].

Improvements in impinging stream (IS) reactors and further research in this field were initiated in the early 1980s by Elperin and Tamir [3], who suggested a new configuration for the reactor in which the inlet streams entered the reactor tangentially, rather than counter-currently on the same axis. Such two impinging streams cyclone reactors (TISCRs) were first designed and studied by Tamir et al. [4].

TISCR has been employed as a chemical reactor to carry out solid–liquid reactions [5] and for dissolution of solid particles in water [6–8]. IS systems have been successfully applied to other chemical processes such as mixing, drying, absorption, desorption, leaching, liquid phase reactions, extraction, crystallization and heat transfer operations [9–31].

The mean residence time of particles in a reactor, τ, is an important parameter indicating whether a certain process or reaction can be carried out to the desired degree of completion. In an impinging stream reactor, the residence time of particles in the impingement zone is one of the more important issues, as such a zone is the active region in enhancing heat and mass transfer between the phases. The hold-up of particles in the reactor essentially quantifies the surface area available for a transfer process, or for the extent to which the actual area of the particles is effective since there is possible

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Table 1
Physical properties of the material.

Property	Values	Comment
Particle density, ρ_p	2500 kg/m^3	Sand
Liquid density, ρ_l	998.2 kg/m^3	Water
Mean particle diameter, d_p	295×10^{-6} m	Uniform distribution

reduction of such an area due to physical contact between the particles at relatively high hold-ups. There are a number of experimental studies confirming such a case [32–35].

The viability of CFD for the design and optimization of chemical reactors has been demonstrated extensively for a wide variety of systems [36–40]. An increasing number of studies have reported the use of CFD modeling to estimate values of important properties needed for reactor design, such as the mean residence time of particles, hold-up and residence time distribution in reactors [41–45]. Extensive investigations have been performed concerning CFD modeling of mean residence time and holdup of solid particles in diverse types of contactors, however, it seems that no study has yet been reported on CFD modeling of the latter parameters in impinging streams reactors.

Devahastin and Mujumdar performed dynamic simulations to assess fluid–fluid mixing in different Reynolds numbers and IS geometries [46]; Wang and Mujumdar have reported three dimensional CFD simulations using the Reynolds-Averaged Navier–Stokes equations for 3D T-jet mixers with different jet flow rates [47]. Wang et al. investigated steady state simulations of planar T-jets mixers with equal and unequal jets flow rates with fluids having different temperatures [48].

The main goal of this study is to measure both the mean residence time and holdup of particles in a TISCR, and to compare the CFD predictions with experimental data. By application of the CFD technique the behavior of complex systems influenced by a large number of flow, fluid and geometric parameters can be predicted cost-effectively with minimum data requirement. A successfully validated CFD model can be used for reliable design and prediction of off-design performance as well as optimization of reactor performance.

2. System simulation

In this work the holdup of solid particles and the mean residence time in TISCR have been simulated using a commercial CFD software package. The experimental data used in this study were taken from a previous study of Sohrabi et al. [49]. Briefly, the reactor consisted of a cylindrical reaction chamber with an inner pipe creating an annular space and directing the streams towards the impingement zone. The solid phase was fed to the fluid stream and the two streams of suspension (fluid and solid) were fed through symmetrically positioned accelerating pipes. The accelerated suspension feed streams impinged in the annular space and dropped instantly along the inner discharge tube down to the outlet port. To determine the mean residence time of particles within the system, sand with 2500 kg/m^3 solid density was used as the solid phase and water as the fluid phase (Table 1).

Measurement of the mean residence time of the liquid and the solid phases in the reaction system requires knowledge of the liquid and solid holdups within the reactor, respectively. A most widely used technique for holdup estimation in various types of reactors is the so-called "shutdown procedure". Following the shutdown procedure, water and sand particles were introduced continuously at pre-selected volumetric and mass-flow rates, respectively, into the reactor. After establishment of steady-state conditions, the flows of water and sands were suddenly halted and the material remaining in the reactor were collected [50]. A schematic diagram of the TISCR with detailed geometric dimensions is shown in Fig. 1 and Table 2.

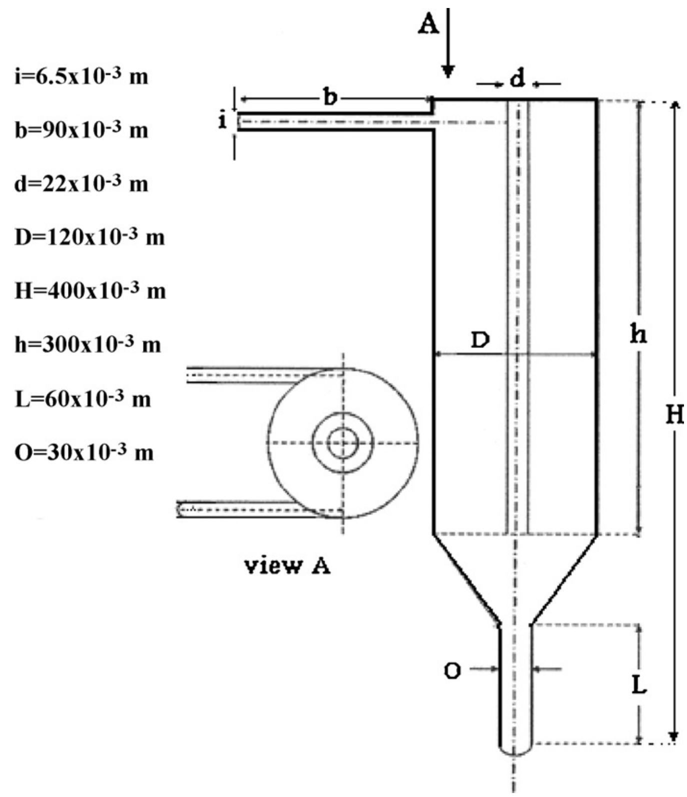

Fig. 1. Definition of TISCR dimensional parameters used by Sohrabi et al. [49].

GAMBIT 2.3.16 is a software used to mesh the 3D flow domain (Fig. 2). To ensure grid independency of the CFD results, three mesh designs (22,168, 82,222and 192,200 cells) were tested for the TISCR simulations. The results indicated that the data for flow velocities were independent from the number of cells of the grid. The CFD software package, Fluent (V6.3.22), was then used to solve the conservation of mass and momentum equations for the specified geometries.

Water at 293 K was selected as the operating fluid. Inlet velocities, 10% turbulence intensity, and a uniform velocity distribution were defined and a fully developed flow (outflow) was applied as the boundary condition at the exit. In all cases, the Standard Wall Function was employed for the turbulent boundary layer in the wall region.

The solver was set up for steady state, coupled and implicit mode to solve the governing equations, starting with first order upwind formulation for the converged solution. The SIMPLE method was chosen for the pressure–velocity coupling. The common method for specification of convergence of the solution is to check and monitor the residuals. Thus, convergence of the numerical solution was ensured by monitoring the scaled residuals of continuity, x, y and z

Table 2
Dimensions of the two impinging streams cyclone reactor (TISCR).

Description	Values
TISCR diameter, D (m)	0.120
Outlet diameter, O (m)	0.030
Inlet diameter, i(m)	0.0065
Distance between the inlets and reactor, b(m)	0.090
Inner tube diameter, d (m)	0.022
Inner tube height, H(m)	0.300