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Ejector type solid circulation system analysis for circulating fluidized beds

Serhat Gül[a,b,*], Z. Sibel Özdoğan[b]

[a] TUBITAK Marmara Research Center Energy Institute, 41470 Gebze, Kocaeli, Turkey
[b] Marmara University, Goztepe Campus, Department of Mechanical Engineering, 34722 Kadikoy, Istanbul, Turkey

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ABSTRACT

Proper solid circulation is of crucial importance for the stable operation of circulating fluidized beds. There should be a pressure barrier between the riser and the downcomer to avoid reverse gas flow through the downcomer and to maintain a stable solid circulation. In conventional systems, loop seals, L, J, V, valves are mostly used as solid circulation valves. In this study, ejector (eductor) type solid circulation was investigated in an experimental CFB setup (94 mm in diameter, 7950 mm in height). The solid flux at the downcomer (34 mm in diameter) and the motive gas flowrate of the ejector were investigated under different cold flow conditions. There are two different operation modes of the ejector type solid circulation depending on the solid flux through the downcomer. For low solid fluxes, there is no solid accumulation at the downcomer. As the solid flux increases, a solid column formation is observed above the ejector system. The desired pressure difference obtained with the ejector is higher for the latter mode of operation and requires less motive gas flow compared to the former for proper operation. The experimental results show that the ejector is capable to provide the required pressure barrier for the CFB loop in both cases. In addition to the experimental study, ejector system was analyzed with CFD model in order to investigate the effect of basic geometric and operational parameters on the pressure difference generated by the ejector. Furthermore a novel semi-empirical method was proposed as a tool for predicting the ejector performance comparable with CFD results.

1. Introduction

Circulating fluidized beds (CFB) are widely used for thermal processes, such as drying, combustion, gasification and mineral processing. Contrary to the bubbling fluidized bed systems which are generally preferred for small scale applications (Higman, 2003), solids must be circulated in circulating fluidized bed systems. Circulation systems are considered as the heart of a CFB system from the viewpoint of its importance and its functions. Poor circulation may result in heat transfer and/or reaction problems along with mechanical problems leading to shut down of the system. It has been reported that the major problem in CFB operation is the interruption of solids circulation through the CFB loop. Therefore, proper operation of solids circulation system is of crucial importance for the stable operation of CFB reactors (Kim and Kim, 2002).

Generally, the circulation loop of a CFB system consists of a riser, a cyclone separator, a downcomer and a solid flow control valve. A pressure barrier is necessary to prevent gas flow from the riser to the downcomer so that a stable solid flow is maintained from the downcomer to the riser. At commercial scale applications, the common circulation valve is loop seal which is a non-mechanical valve without any moving parts. Basically, it is a bubbling fluidized bed used for providing a pressure barrier between riser and downcomer. If the operation of the loop seal stops, solids accumulate in the downcomer and in the cyclone leading to an interruption in the solid flow from cyclone to the riser. Sometimes the accumulated large amount of solids may suddenly flow into the bed causing massive fluctuations in bed pressure. If the solid inventory in the loop seal is too low to create a pressure barrier a reverse gas flow occurs to the cyclone from the riser through the downcomer and reduces the cyclone efficiency (Basu, 2006; Basu and Butler, 2009). For both cases, the entire system may have to be stopped to get proper start up conditions.

The proposed alternative CFB concept is based on an ejector (eductor) placed at the downcomer of the CFB system (Gul et al., 2015). The pressure difference required for uninterrupted solid circulation can be achieved and/or rebuilt whether there is initial bed material or not and without the need to re-start the entire system. Therefore, the proposed concept is expected to enable

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* Corresponding author at: TUBITAK Marmara Research Center Energy Institute, 41470 Gebze, Kocaeli, Turkey. Fax: +90 262 641 23 09.
E-mail address: serhat.gul@tubitak.gov.tr (S. Gül).

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Nomenclature

A_d	ejector nozzle cross-section area (m^2)
A_D	ejector tube cross-section area (m^2)
C_D	ejector tube diameter correction factor
C_p	specific heat of motive gas (J/kg K)
C_{Ma}	Mach number correction factor
D	ejector tube diameter (m)
k	specific heat ratio
$\dot{m}$	motive gas mass flowrate (kg/s)
Ma	Mach number
P_e	motive gas nozzle exit static pressure (Pa)
R	specific gas constant (/kg.K)
T_a	temperature of the motive gas at the inlet of the ejector nozzle (K)
T_e	temperature of the motive gas at the exit of the ejector nozzle (K)
V	volumetric flow rate of the motive gas (Nm^3/h)
$\dot{V}_e$	volumetric flow rate of the motive gas at the exit condition of the ejector nozzle (m^3/s)
V_e	motive gas nozzle exit velocity (m/s)

continuous high speed gas flow and continuous solids circulation through the ejector forming a pressure barrier enabling increased uninterrupted operation time of the entire system.

Ejector applications first appeared in 1858, based on the invention by Henry Giffard (Kshirsagar and Deshmukh, 2013) for the purpose of feeding water to the boiler of a steam engine of a locomotive. There are various kinds of ejector applications in the current industry such as, distillation in chemical and petroleum industry, evaporation and drying in food industry, pneumatic conveying or tank drains, vacuum test chambers in aerospace research, refrigeration systems and thermal power plants.

In contrast to the widespread application of ejectors in industry, there is only scarcely available data in the published literature about design and operation of an ejector type circulation system for CFBs. There are some related patents about ejector systems used for capturing fine particles but none of them is used for forming a pressure barrier at CFBs (Vowe, 1972; Bituminous Coal Research, 1975; Yoshio, 1987; Per and Asea Stal, 1988; Dumain et al., 1989; Takashi and Akira, 1998; Anderson et al., 2001; Yoshiro et al., 2003; Howard et al., 2010). Thus, a good understanding of the performance of the ejector type circulation system for CFBs is essential for a preliminary evaluation of the ejector type circulation systems. The present work attempted to develop a first level understanding of the proper design and operational conditions of an ejector type CFB system, by using an experimental CFB cold model.

In addition to the experimental study, computational fluid dynamics (CFD) model was built for the gas only homogeneous case by using CFD simulation software tool FLUENT. A reference ejector system has been built to validate the CFD results. Performance analyses of ejector system depending on the basic geometric and operational parameters (ejector tube length and diameter, nozzle diameter, motive gas flowrate and motive gas temperature) were investigated with CFD model. Furthermore a novel semi-empirical method was proposed as a tool for predicting the ejector performance comparable with CFD results.

Generally, ejector systems are used for the refrigeration systems and the CFD analyses have been focused on mainly jet ejector system for refrigeration cycle (Chan and Chen, 2000; Rusly et al. 2005; Kandakure et al.; 2005; Bartosiewicz et al. 2005, 2006; Zhu et al. 2009; Pianthong et al. 2007; Sriveerakul et al. 2007;Hemidi et al. 2009a,b; Varga et al. 2009a,b; Ji et al. 2010; Varga et al. 2011; Li and Li, 2011; Ruangtrakoon et al. 2013; Varga et al. 2013;Ju et al., 2015). The ejector geometry investigated in this study is different from the ejectors used at refrigeration systems. However, the operations are based on the same physics. The main difference between conventional ejectors and the ejector studied in this paper is the throat/nozzle area ratios. Generally, the area ratios of throat/motive gas nozzle are between 6.4 and 10.6 (Rusly et al., 2005). However, the area ratios studied in this work is in between 25 and 660. The higher area ratios cause lower pressure difference with respect to conventional ejector which is high enough for the operation of the CFB systems. Motive gas nozzle exit velocities/Mach numbers are similar to the conventional ejectors. The CFD analyses of ejector used at refrigeration cycles are mainly supersonic (Sriveerakul et al., 2007; Hemidi et al., 2009a,b). There are various studies in published literature related to conventional ejector systems and mainly focus on the effect of nozzle throat to constant section area ratios, converging angle, operating pressure, mixing tube length, motive gas flowrate, throat diameter and working fluids (Bartosiewicz et al., 2006; Varga et al., 2009a,b; Ji et al., 2010; Li and Li, 2011; Natthawut Ruangtrakoon 2013; Varga et al., 2013). The main performance parameter for conventional ejectors is the entrainment ratio (Kandakure et al., 2005; Bartosiewicz et al., 2005). In this study, validated CFD model was used for investigation of ejector operational and geometric parameters which are outside the experimental range of CFD validation experiments (Rusly et al., 2005; Zhu et al., 2009). Due to the symmetric geometry of ejector, 2D axisymmetric space was chosen (Pianthong et al., 2007; Varga et al., 2011). The realizable $k-\epsilon$ model was chosen as turbulence model in this paper (Varga et al., 2009a,b; Varga et al., 2011).

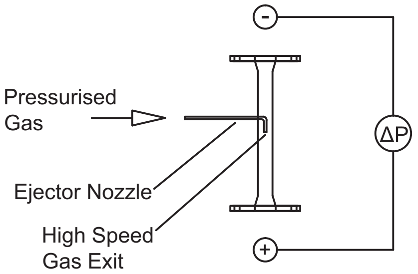

Fig. 1. General principle of the experimental Venturi ejector.

2. Ejector type solid circulation approach for CFB systems

The proposed circulation concept is based on the formation of ejector type pressure barrier. Within this frame, an ejector is placed at the downcomer of the CFB system. An ejector (Fig. 1) is a vacuum generating apparatus, generally driven by compressed gas or liquid. Venturi effect is the main principle which the ejector is based on. Pressurized gases flow at a high speed through the ejector nozzle exit which is parallel to the downcomer. The pressure of the motive gas is converted to velocity which decreases the pressure level at the high velocity region. The momentum transfer by the high speed gas flow at the ejector nozzle exit to the low speed gas flow at the downcomer causes the pressure difference through the ejector system and builds a pressure barrier.

There are 2 different operation modes (Fig. 2) depending on the operational motive gas velocity and the solid flux through the downcomer. In the first mode, there is no solid accumulation through the downcomer because of the low solid flux. The pressure barrier is obtained by the momentum transfer of high speed gas flow at ejector nozzle exit to the low speed gas flow at the downcomer. In contrast to the conventional circulation systems, some amount of gas is being recirculated to the reactor due to the pressure difference formed by the ejector. Under these conditions,