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# Using conical reactor to improve efficiency of ethanol steam reforming

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ABSTRACT

Fixed-bed reactor is one of the most common reactor types applied in ethanol steam reforming (ESR). Despite the low price, easy application and simple structure, low efficiency is considered as one of the most important challenges for these reactors. Using micro scale structure reactors, new and optimized catalysts, and also micro channels with various arrangements, are some of various procedures that have been used to solve this problem. In this work, for the first time, using ESR, the effect of changing reactor diameter in the longitudinal direction of reactor on the performance of fixed-bed microreactor has been studied. In this way, three reactors A, B and C with conical, cylindrical and inversed conical geometry with equal volumes have been used. The effect of temperature, contact time and S/E ratio on ethanol conversion and productivity of $H_2$ and $CO_2$ have been studied. According to the results, conical reactor has the best performance between mentioned reactors.



## Introduction

Nowadays, paying attention to new and renewable energy sources that can be replaced with existing and current fossil fuels is one of the most important and notable subjects. Within the substitutable sources of the energy, hydrogen is a suitable source for power unit in small size fuel cells, mainly the Proton-Exchange-Membrane Fuel Cell (abbreviated as PEMFC) types [1–3]. Some of its advantages have developed many applications for this fuel, such as the replacement of batteries in portable electronics, in auxiliary power units and also in transportation [4]. Many advantages of ethanol convert this fuel to a useful feed for hydrogen production [5,6]: (1) Its production Capability from environmental process and transform to eco-friendly material, (2) Its high H/C ratio within the liquid hydrocarbon feed, (3) Lower toxicity than methanol, (4) Easy transportation.

Ethanol steam reforming (ESR) is one of the effective and prevalent methods for hydrogen production: no need to oxygen supplying, high $H_2$/CO ratio for hydrogen production and possibility for regulation of process condition (prevention from coking, etc.) are the most useful advantages of this method.

Ethanol steam reforming is a complicated process. The efficiency of this process can be identified as various parameters like ethanol conversion, hydrogen production and heat consumption. Its efficiency is dependent on various parameters. Process conditions, catalyst, reactor type and construction are the main factors that influence the efficiency of this process. Many literature have studied the mentioned factors. Most of them focused on process conditions and catalysts used in this process [2–7].

Various reactor types have been used in ethanol steam reforming. Membrane reactor is one of them. In this reactor,

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using the membrane and the ability to separate products in reactor (where the reaction occurs), leads into the production of hydrogen with high purity [8,9]. Fluidized bed is another type that has been used in this process [10].

Simplicity of structure, easy application, low construction price and low amortization, have introduced fixed bed reactor into one of the most applicable reactors used for ESR. However, they have lower efficiency than other types like membrane reactor and fluidized bed reactor [11]. Many solutions have been used to increase the efficiency of fixed-bed reactors. Micro reactor is one of the structures developed to enhance the efficiency of fixed bed reactor [12]. Teongfei et al. investigated oxidative steam reforming of ethanol in micro channel reactor with $Ir/CeO_2$ and reported that performance of micro reactor is higher than fixed bed reactor [13]. Using micro reactor instead of fixed bed reactor resulted in increasing ethanol conversion from 87 to 97% at 350 °C. High ratio of surface to volume of micro reactors creates specific properties related to heat and mass transfer for them.

Most parts of literature about reforming in fixed-bed reactors are about the geometry of Flow channel and reactor. In some of these studies, overall changes in reactor geometry or the modification of pattern flow have been studied. In some cases, using different heating source to provide the required heat reaction resulted in improved reactor efficiency.

Chen et al. have used a construal tree-shaped network to design a microreactor with three-dimensional model for methanol steam reaction [14]. In this work they evaluated and compared performance of tree-shaped reactor with serpentine reactor. Methanol conversion, CO concentration and the total pressure drop have been evaluated in both reactors. The result of their study indicated that conversion rate of the constructal microreactor is more than 10% over that of serpentine reactor. Yao et al. used three-dimensional model to study a disc microreactor with constructal tree-shaped flow [15]. Performance of this reactor is compared with parallel flow pattern microreactor by using methanol steam reforming. The feed conversion and yield of hydrogen production in the product of the microreactor have been investigated and compared. The effects of branching level, steam to methanol ratio (SMR), and inlet velocity on the reaction performance of the microreactors are investigated. Their results indicated that using disc tree-shaped microreactor instead of parallel one resulted in 10% increasing for methanol conversion. In addition larger branch level causes enhanced performance in the methanol conversion and hydrogen production for disc tree-shaped microreactor. In other work, Chen et al. investigated three-dimensional model for methanol steam reforming in fractal tree-like micro channel network [16]. The effects of process condition and bifurcation angle on the micro reactor performance and mass transfer were investigated in spiral and tree-like reactor. The results showed that branching has important effect on mass transfer and reaction progressing. Also fractal tree-like geometry had better performance than spiral plate reactor. They also investigated the effect of temperature and bifurcation angle in fractal tree-like reactor. They showed that bifurcation angle doesn't have much effect on reaction progress. Yan et al. studied a spiral multi-cylinder micro-reactor for the mobile fuel cell applications theoretically [17]. They optimized performance conditions for methane auto thermal reforming. An et al. investigated flow arrangement in micro channels with simulation [18]. Eight different configurations of coiled micro reactor have been studied. The used coils had square cross-section. These configurations include parallel, pin-hole, wavy, oblique fin, serpentine, coiled, coiled with serpentine and coiled with double serpentine channel geometries. These micro channels have been studied in the wide range of Reynolds number. Their study showed that the best overall performance was obtained for pinhole channel design. Performance of a bench-scale annular microchannel reactor has been investigated by Butcher et al. [19]. They studied steam reforming of methane in this reactor. Special flow patterns have been used for reforming and combustion channel. Bayat et al. studied endothermic and exothermic reactions in heat exchanger reactor [20]. The heat of endothermic reaction is provided with exothermic reaction by exchanging through wall of the reactor. Channel with circular cross section was used in the reactor. A monolith catalytic reactor with jacket was used for reforming reaction [21]. Various conditions for tubular reactor with different catalysts in shell and tube have been investigated. Casanovas et al. studied many micro channels in a reactor geometry [22]. Half of circular micro channels were used in heat exchanger plate geometry. Reforming and combustion reactions happened in micro channels around this plate reactor. Heat of oxidation reaction exchanged from the wall of the micro channel to reforming reaction side. Different catalyst were used for reforming and oxidation channel. Ethanol steam reforming in parallel plate reactor consisting of micro channels with 500–2000 μm width was studied by Bruschi et al. [23]. Cross sections of micro channel were squared. Endothermic reforming reaction in co-current and counter-current flow occurred in proximity of hot flue gases of combustion reaction. Performance of the reactor was investigated in various cases. The effect of channel width on the efficiency of the reactor has been studied. Andisheh Tadbir et al. did numerical simulation for methanol steam reforming in micro reactor [24]. They investigated reforming and combustion in separate micro channels with different catalysts. The effects of catalyst thickness and GHSV for reforming and combustion channel were studied. In their work micro channel with rectangular cross section for both reactions has been used. In another work [25] reforming and combustion of methanol in micro channels were studied. Many micro channels with square cross section in rows and columns have been studied. The effects of process condition like GHSV, S/C ratio on methanol conversion and hydrogen production have been investigated.

Some of the literature have focused on geometrical parameters of the reactor. Kurnia et al. simulated methane oxidation in reactor with various cross sections and spiral plate [26]. Circular, half circular, rectangular, triangular, square and trapezium with equal cross section area were investigated. Different Reynolds numbers were used in this study. The effect of changing surface geometry and Reynolds number on mass transfer and reaction were investigated. Also two structures of reactor consisting of spiral and direct channels were studied and compared. Uriz et al. have carried out three-dimensional simulation study for ethanol steam reforming (ESR) [27]. The cross sections of the channels were