Title

Continuous and efficient production of hydrogen from methanol in protruded millisecond microchannel reactors for fuel cell applications

Author

Chen, Junjie

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Junjie Chen [a, b, *]

[a] Department of Mechanical and Aerospace Engineering, College of Engineering, University of California, Davis, California, 95616, United States

[b] Department of Energy and Power Engineering, School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo, Henan, 454000, P.R. China

* Corresponding author, E-mail address: junjiem@tom.com

Abstract

Protrusions can be used to improve the transport processes involved, but the causes of the phenomena are still incompletely understood. Computational fluid dynamics analyses are performed under different sets of circumstances to gain insights into the physics of heat and mass transfer processes in a protruded millisecond microchannel reactor, wherein a steam reforming reaction is proceeding and protrusions are used to improve the transport processes involved. Recommendations are made on how to optimize design for better reactor performance. Particular emphasis is placed on delineating the role of methanol-air equivalence ratio and channel length in reactor performance. The results indicate that the equivalence ratio and channel length must be adjusted as needed to minimize pressure drops and maximize production of hydrogen. Necessary adjustments to the equivalence ratio of methanol to air can be made to control the maximum reactor temperature within certain needed limits. The short-channel design may be preferred over the long-channel design in order to simultaneously achieve low pressure drops and sufficiently high conversions in the reactor. Expectable compromises have to be made between hydrogen productivity and pressure drop.

Keywords: Equivalence ratios; Channel lengths; Fuel cells; Flow configurations; Heat fluxes; Heat exchange

1. Introduction

A fuel cell is an electrochemical system in which a fuel is reacted with an oxidant at high temperature to generate electricity [1, 2]. One type of fuel cell is the solid oxide fuel cell. The basic components of a solid oxide fuel cell may include an anode, a cathode, an electrolyte, and an interconnect [3, 4]. The fuel may be supplied to the anode, and the oxidant may be supplied to the cathode of the fuel cell. At the cathode, electrons ionize the oxidant [5, 6]. The electrolyte may comprise a material that allows the ionized oxidant to pass therethrough to the anode while simultaneously being impervious to the fluid fuel and oxidant [7, 8]. At the anode, the fuel is combined with the ionized oxidant in a reaction that releases electrons that are conducted back to the cathode through an external circuit or to the cathode of an adjacent solid oxide fuel cell via the interconnect.

A solid oxide fuel cell may be structured, for example, as a segment-in-series or in-plane series arrangement of individual cells [9, 10]. The oxidant is typically introduced at one end of the series of cells and flows over the remaining cells until reaching the cathode exhaust outlet [7, 8]. Each fuel cell transfers heat into the oxidant thereby raising its temperature, and forming a temperature gradient which increases from the oxidant inlet to the exhaust [7, 8]. A temperature gradient may also develop in the fuel cell which increases from the oxidant inlet to the oxidant exhaust [11, 12]. These temperature gradients cause thermal stresses that may cause material degradation or failure of the fuel cell components, or may reduce fuel cell performance.

The anode of a solid oxide fuel cell may be a mixed cermet comprising nickel and zirconia or nickel and ceria [13, 14]. Nickel, and other materials, may function not only to support the chemical reaction between the fuel and the ionized oxidant but may have catalytic properties which allow the anode to reform a hydrocarbon fuel within the fuel cell [15, 16]. One method of reforming the hydrocarbon fuel is steam reforming of methane [17, 18]. The heat necessary for methane steam reforming could be supplied directly from the heat released within the stack from the ohmic losses. This direct heat transfer helps to cool the stack, reducing thermal stresses and improving overall stack performance. However, in-stack reforming introduces several technical challenges [19, 20]. The unreformed methane must be supplied in the correct amount to avoid excessive cooling of the fuel cell and in the correct manner to avoid localized cooling. Additionally, hydrocarbon fuels have a propensity to form carbon, particularly when a significant amount of reforming is performed.

Carbon formation can cause fouling and degradation of fuel cell components [21, 22]. Consequently, supplying a mixture of a syngas reformed external to the fuel cell and an unreformed fuel to the anode may provide a better balance of system performance and durability than supplying either reformate or unreformed fuel alone. However, the ratio of reformed and unreformed fuel must be precisely controlled [23, 24]. If the ratio is too high, the large temperature gradient across the fuel stack will remain. If it is too low, carbon formation will result in loss of performance. There remains a need for precise control of the ratio of reformed and unreformed fuels delivered to a fuel cell stack to ensure that the proper amount of reforming occurs internally to the fuel cell.

Hydrocarbon reforming takes place in the presence of steam and the steam to carbon ratio in the gas stream to the reformer is one of the most critical variables in the reforming reaction [25, 26]. Furthermore, the presence of steam in the fuel stream to the fuel cell can prevent carbon deposition on the catalyst used to effect internal reforming [27, 28]. Accurate control of the steam to carbon ratio is therefore an important consideration. It is important for effective and efficient operation of a fuel reformer that the steam and fuel to be processed are delivered at a suitable rate. Invariably, the steam is delivered to the reformer under pressure from a steam generator, such as a water boiler, with appropriate flow control as required [29, 30]. Gaseous fuel may be delivered under pressure directly from a bottled source. In this case accurate control of the steam to carbon ratio in the gas stream to the reformer requires careful control of the flow of both the steam and fuel components [31, 32]. In turn this may require complex monitoring and control systems. It would be desirable to provide a fuel cell system that allows the steam to carbon ratio to be controlled in a more straightforward manner.

In steam reforming processes, steam and hydrocarbons react to produce hydrogen, as well as carbon monoxide, carbon dioxide and methane. This chemical process takes place in a steam reformer, when a mixture of steam and hydrocarbons are subject to high temperatures while flowing through a catalyst filled zone [33, 34]. Steam reforming is a highly endothermic process as the chemical reaction absorbs heat, and thus steam reformers are often supplied with combustion systems for producing the necessary thermal energy required in the chemical process [35, 36]. Although fuel cells provide a highly efficient power source, the production of hydrogen involves energy consumption for supplying heat to the endothermic reaction, for producing steam to be mixed with the hydrocarbons [37, 38]. In order to render the production of hydrogen efficient, it would be desirable to minimize the energy consumed in the production of the hydrogen [39, 40]. Accordingly, it would be desirable to provide a highly integrated steam reformer, namely a steam reformer maximizing the recuperation of the heat produced to supply the endothermic reaction of steam reforming.

In the present study, computational fluid dynamics analyses are performed under different sets of circumstances to gain insights into the physics of heat and mass transfer processes in a protruded millisecond microchannel reactor, wherein a steam reforming reaction is proceeding and protrusions are used to improve the transport processes involved. Recommendations are made on how to optimize design for better reactor performance. Account is taken of the factors that may influence the performance of the protruded reactor. The present study aims to understand the causes of the phenomena of process intensification in a protruded reactor. Particular emphasis is placed on delineating the role of methanol-air equivalence ratio and channel length in reactor performance.

2. Model development

Scientific modelling is the generation of a physical, conceptual, or mathematical representation of a real phenomenon that is difficult to observe directly. Scientific models are used to explain and predict the behaviour of real objects or systems and are used in a variety of scientific disciplines [41, 42]. There are numerous applications for scientific modelling [43, 44]. In the present study, a three-dimensional model of the protruded reactor is used to gain insight into the transport phenomena involved and to assist with reactor design. For a reaction to occur, it is not sufficient that it be energetically product-favoured. Several factors influence reaction rates, including the concentrations of reactants, the temperature, and the presence of catalysts.

2.1. Operation conditions

The design uses protrusions for the reforming channels to improve the transport processes involved. The solution domain of the protruded reactor system is illustrated schematically by reference to Figure 1 with the wall and its surface indicated. The protruded channel comprises an array of hemispherical protrusions extending downstream from the inlet toward the outlet. The structures of the wall and its surface of the reactor utilized for producing hydrogen-rich gas is illustrated schematically by reference to Figure 2 with the hemispherical protrusions indicated. The protrusions provide improvement by increasing the desirable disturbance of the flow over the washcoat coating surface where they are located [45, 46]. Another solution to the protrusions is to improve the transport characteristics by increasing the boundary area [47, 48]. The protrusions are hemispherical in shape and arranged regularly on the wall surfaces to achieve the desired characteristics.

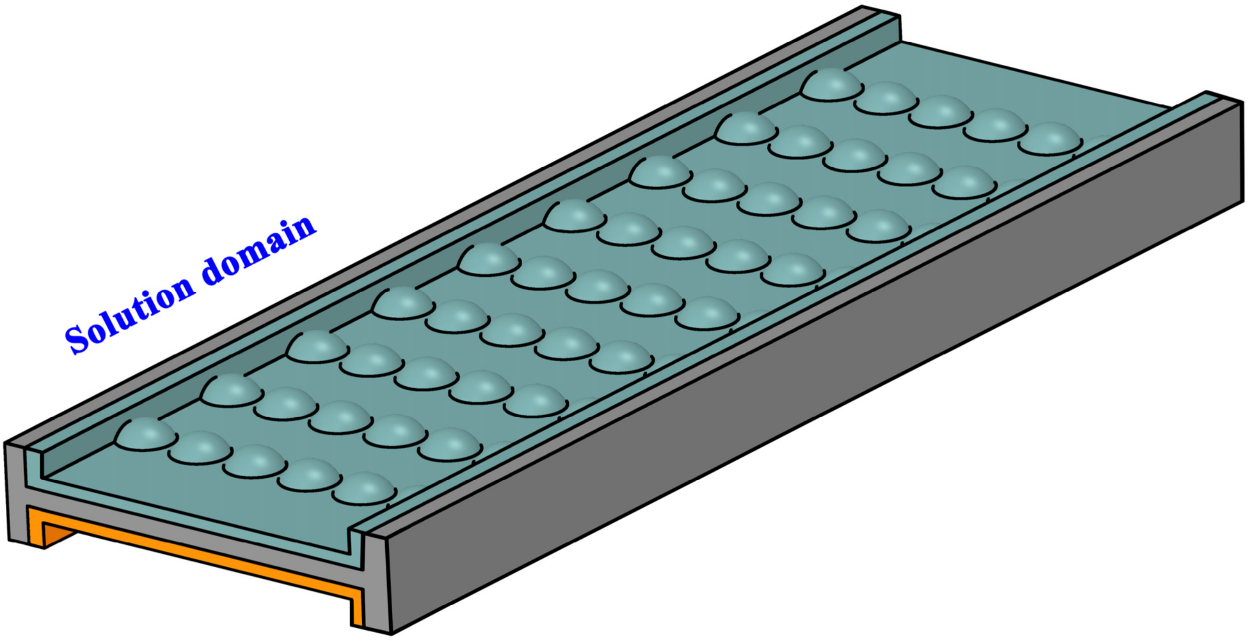


Figure 1. Illustration representation of the solution domain of the protruded reactor system with the wall and its surface indicated. The protruded channel comprises an array of hemispherical protrusions extending downstream from the inlet toward the outlet.

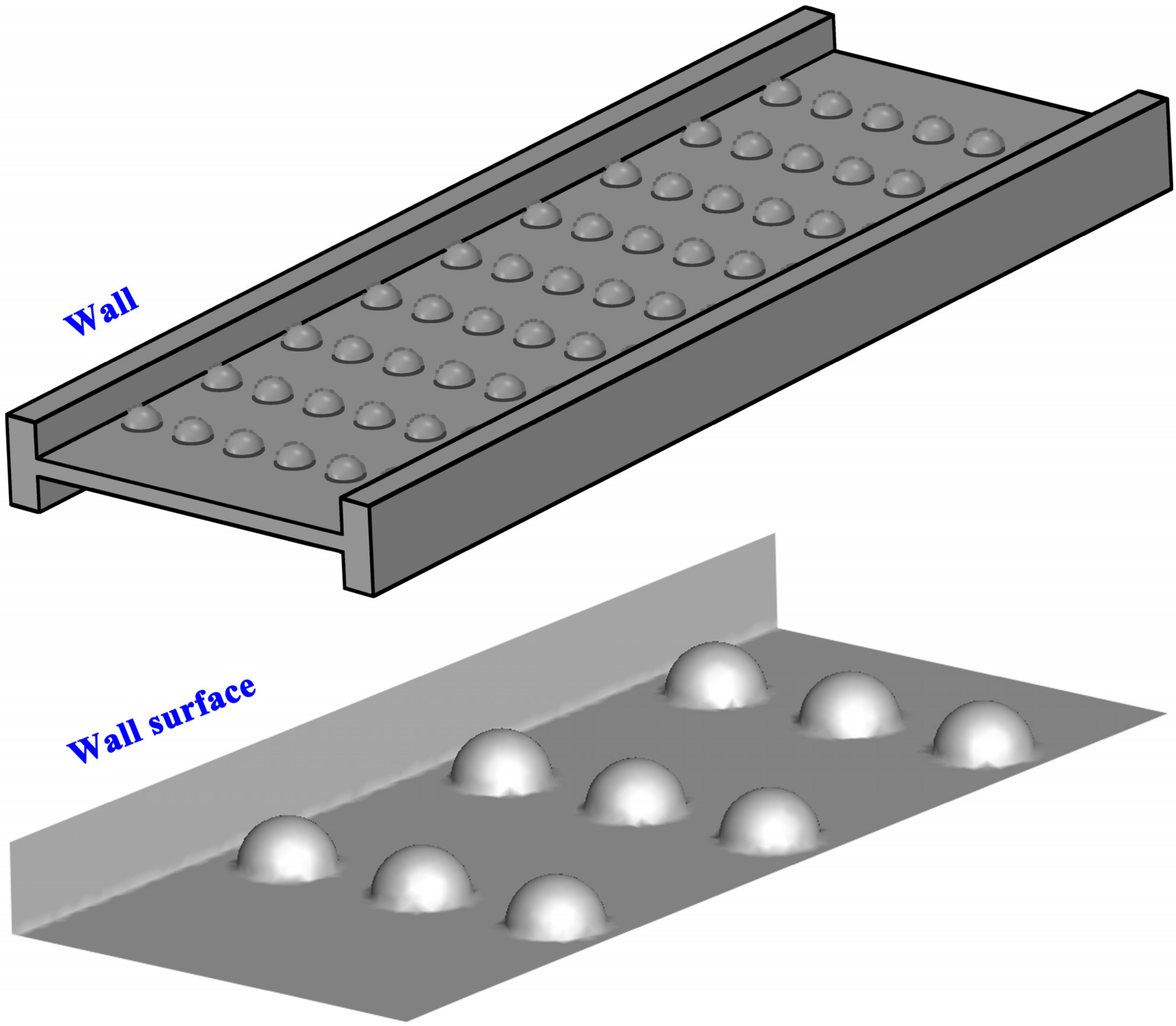


Figure 2. Illustration representation of the structures of the wall and its surface of the reactor utilized for producing hydrogen-rich gas.

The channels are 60.0 mm in length, 5.6 mm in width, and 0.8 mm in height, the washcoat coatings are 0.20 mm in thickness, and the walls are 0.30 mm in thickness, unless otherwise expressly provided. For the feed stream to be reformed or oxidized, the gaseous reactant mixture is supplied to the reactor in a molar ratio of steam to methanol of 150:100 or with an equivalence ratio of methanol to air of 0.8, unless otherwise specified. The reactor operates at one atmosphere pressure with an inlet temperature of 100 °C for both the gaseous reactant mixtures. The gaseous reactant mixtures are introduced respectively into the reactor with a free-stream velocity of 1.2 m/s at the oxidation channel inlet and a free-stream velocity of 4.0 m/s at the reforming channel inlet, unless otherwise noted. The protrusions coated with the reformation catalyst are 1.0 mm in diameter, and the protrusions are 0.6 mm in diameter if they are uncoated.

Hydrogen is produced by steam reforming methanol in a reactor which is shaped much like a conventional shell and tube heat exchanger except that the tubes contain catalysts. In these reactors, hot gases are passed through the shell of the heat exchanger while the vapor of methanol and water is passed through the tubes. Thus, the heat required for the endothermic catalytic reforming reaction must pass through the wall of the tube. In order to improve the thermal and chemical efficiency of such reactors, efforts have been directed to improve the uniformity of heat distribution in the tubes within the reactor to secure high chemical conversion of fuel into hydrogen and maintain catalyst bed temperature within certain limits in order to avoid premature catalyst aging while minimizing the amount of energy used to produce each unit of hydrogen containing gas. For efficient operation of the steam reforming reaction, large surface areas are required to transfer the heat from the combusted gases to the tubes. In reformers presently used for steam reforming, small diameter reaction tubes are clustered closely together in the furnace so that heat transfer from the combusting gases in the reactor into the catalyst packed tubes is optimized. In fuel cell systems in which the reformer and the fuel cell are fully integrated, the shell side heat transfer coefficient between the hot gas and the tube is characteristically low and hence, the rate of reaction is limited primarily by the rate of heat transfer. This problem is particularly severe at the reactor entrance as the rate of the endothermic reaction is very high, and thus, the amount of heat required is very high while the shell side heat transfer coefficient is often low as the mechanical design of typical reactors often allows the gases in the shell to be relatively stagnant near the tube entrances. This leads to a drop in the overall efficiency as a large portion of each reactor tube operates at an undesirably low temperature. Thus, in order to effect complete conversion, the reformer must be relatively large and expensive.

2.2. Mesh sensitivity study

A finite-volume method is used for simulating flow past an array of hemispherical protrusions. A mesh sensitivity study is conducted to determine the dependence of the calculated results on the mesh density and to understand how much the mesh is affecting the solution. Calculations are performed using meshes with different nodal densities. The fluid temperature profiles along the centreline of the oxidation or reforming channel are presented in Figure 3 for meshes with different resolutions. The mesh is refined evenly throughout the entire domain, and the mesh size varies depending upon reactor dimensions. The solution varies for different mesh sizes. The coarsest mesh, which has roughly 72 thousand nodes in total, does not accurately capture the temperature profiles. For the moderate mesh that has roughly 240 thousand nodes in total, the spatial discretization error tends to zero and the calculated results change very little with additional refinement. The fine mesh, which has roughly 470 thousand nodes in total, offers no significant advantage. The solution varies a very small amount between the moderate and fine meshes. The solution to the problem is reached using the moderate mesh in most cases and using the fine mesh for the reactor with the largest dimensions.

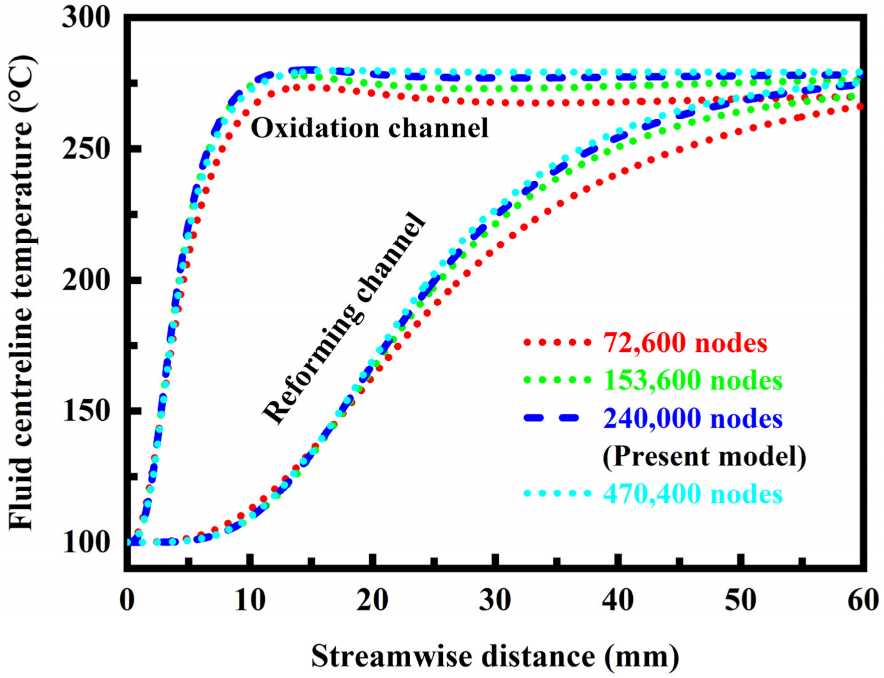


Figure 3. Fluid temperature profiles along the centreline of the oxidation or reforming channel for meshes with different resolutions.

2.3. Model validation

Comparisons between calculations and measurements are carried out to validate the model. The methanol and hydrogen concentrations are measured at the outlet of a microchannel reactor wherein the reforming reaction occurs [49, 50]. The fluid travels through the channels in laminar flow and the reactor is constructed of eight plates of stainless steel. Calculations are performed using the model described above for the reactor under certain operation conditions. Comparisons between the calculated and measured data, including methanol conversion and hydrogen productivity, are performed at different wall temperatures. The comparison results are presented in Figure 4 at different flow rates of the liquid feed at room temperature. The calculated data are in reasonably good agreement with the measured data in the wall temperature range specified.

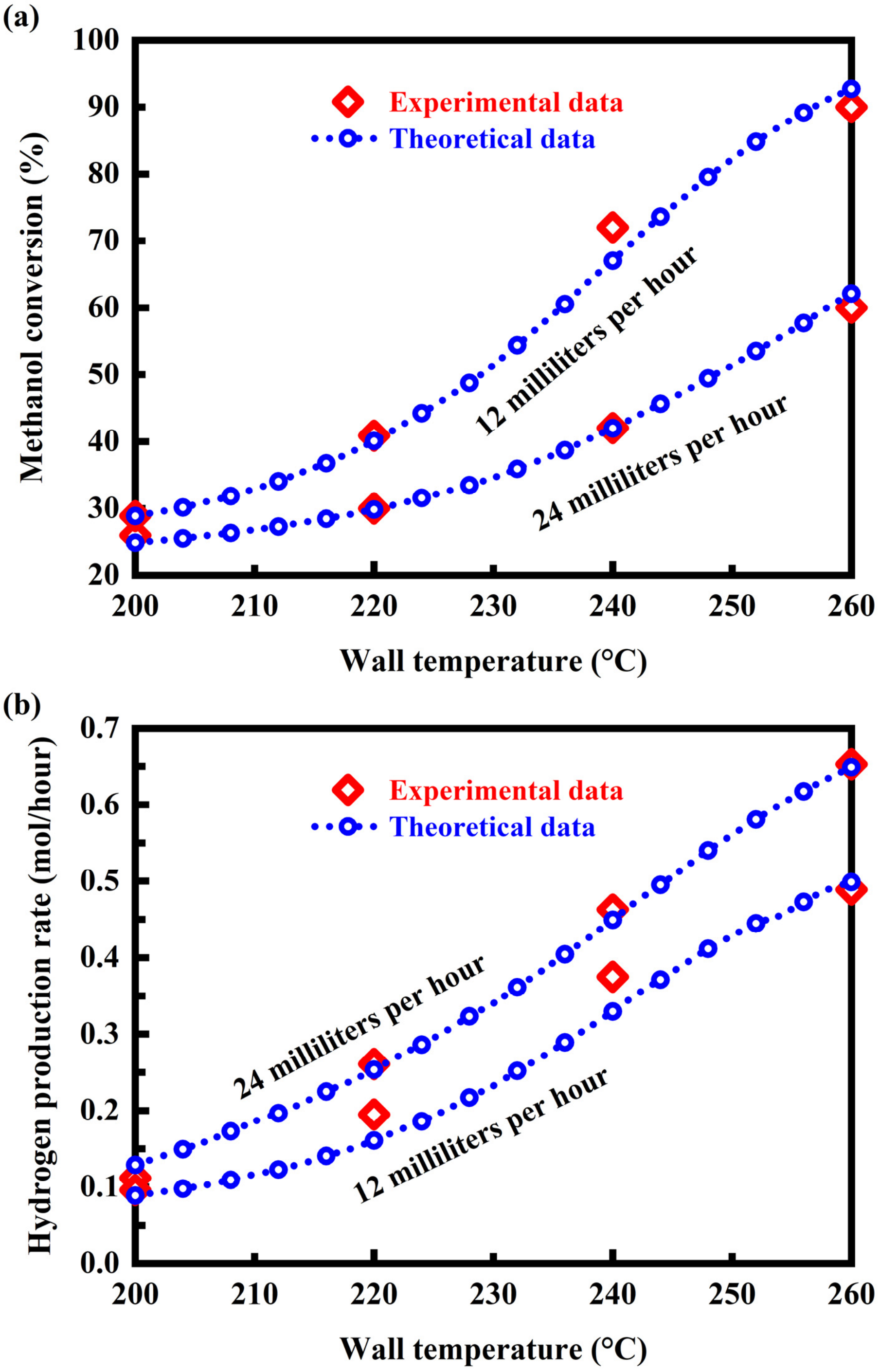


Figure 4. (a) Comparisons of theoretical and experimental methanol conversion at different wall temperatures and flow rates. (b) Comparisons of theoretical and experimental hydrogen productivity at different wall temperatures and flow rates.

3. Results and discussion

Combustion, with rare exceptions, is a complex chemical process involving many steps that depend on the properties of the combustible substance. Combustion encompasses a great variety of phenomena with wide application in industry and the sciences, and the application is based on knowledge of physics, chemistry, and mechanics. Their interrelationship becomes particularly evident in treating flame propagation. In general terms, combustion is one of the most important of chemical reactions and may be considered a culminating step in the oxidation of certain kinds of substances. In addition to chemical reactions, physical processes that transfer mass and energy by diffusion or convection occur in gaseous combustion. In the absence of external forces, the rate of component diffusion depends upon the concentration of the constituents, pressure, and temperature changes, and on diffusion coefficients. The latter are either measured or calculated in terms of the kinetic theory of gases. The process of diffusion is of great importance in combustion reactions and in flames. Diffusion heat transfer follows a law stating that the heat flux is proportional to the temperature gradient. The coefficient of proportionality, called the thermal conductivity coefficient, is also measured or calculated in terms of the kinetic theory of gases, like the diffusion coefficient.

The principal quantitative characteristic of a flame is its normal, or fundamental, burning velocity, which depends on the chemical and thermodynamic properties of the mixture and on pressure and temperature, under given conditions of heat loss. The burning velocity value ranges from several centimetres to even tens of metres per second. The dependence of the burning velocity on molecular structure, which is responsible for fuel reactivity, is known for a great many fuel-air mixtures. A widely applied thermal theory, one of the first flame propagation theories, implies that combustion proceeds primarily at temperatures close to the maximum the flame can achieve. A set of differential equations developed for thermal conductivity and diffusion is reduced to one equation that yields the burning velocity value. Further development of the theory has been made, and computers now make most simplifications unnecessary. According to thermal theories, flame propagation is accounted for by heat energy transport from the combustion zone to the unburned mixture, which raises the temperature of the mixture. Diffusion theory assumes that thermodynamic equilibrium sets in behind the flame front at a maximum temperature and that radicals produced in this zone diffuse into the unburned mixture and ignite it. Both heat transport and diffusion of active particles must be considered essential for ignition.

3.1. Effect of methanol-air equivalence ratio

The equivalence ratio is a well-established metric used to evaluate a fuel-air mixture in combustion. Since its inception, this metric has been used to evaluate the reactive properties of gas mixtures and their impact on combustion. The term "equivalence ratio" is used to denote the proportions of methanol and air in the mixture. The equivalence ratio is defined as the ratio of the actual methanol-air ratio to the stoichiometric methanol-air ratio, at which the stoichiometric coefficients are calculated for the reaction giving full oxidation products. An equivalence ratio less than one defines a fuel-lean mixture, and an equivalence ratio greater than one defines a fuel-rich mixture.

Calculations are performed using computational fluid dynamics at equivalence ratios greater than 0.6. The temperature profiles along the centreline of the oxidation or reforming channel are presented in Figure 5 at different equivalence ratios of methanol to air. An equivalence ratio of one is stoichiometric, and excess air is typically required to achieve complete oxidation for the reaction [51, 52]. A lean or super-stoichiometric mixture contains more air than the amount theoretically required for complete oxidation, and has an equivalence ratio of less than one. The reverse applies for a rich or sub-stoichiometric mixture. Necessary adjustments to the feed compositions, for example, the equivalence ratio of methanol to air, can be made to control the maximum reactor temperature within certain needed limits. Oxidation under stoichiometric or substantially stoichiometric conditions may be advantageous, as the temperature of the feed stream can be greatly increased prior to reformation, for example, in excess of 300 °C. However, the reactor is preferably operated in such a way as to control the temperature of the entering gas stream over the washcoat coating surface in the range from 200 °C to 300 °C. A variation in the temperature outside this range may cause undesired side reactions to occur within the reactor [53, 54]. Furthermore, the heat produced under stoichiometric or substantially stoichiometric conditions may damage the washcoat coating and other portions of the reactor, and may result in deactivation of the catalytically-active components [53, 54]. A lean or super-stoichiometric mixture is preferably supplied to the reactor so that sufficient oxidation intensity can be achieved while maintaining a desired temperature range of the process flow stream. At compositions closer to the lower limit of flammability, however, a problem with stability arises [55, 56], as the overall temperature is substantially lowered. In particular, additional air serves to absorb heat produced by the oxidation reaction, therefore enabling a lower, overall temperature to be achieved in the reactor. Temperatures greater than 200 °C are often required to achieve a practical conversion level. Rich mixtures tend to lower the overall temperature, and a problem with cost arises, as the fuel is excessively supplied. Consequently, the amount of air supplied to the reactor must be closely controlled to avoid deviations from the optimum equivalence ratio conditions.

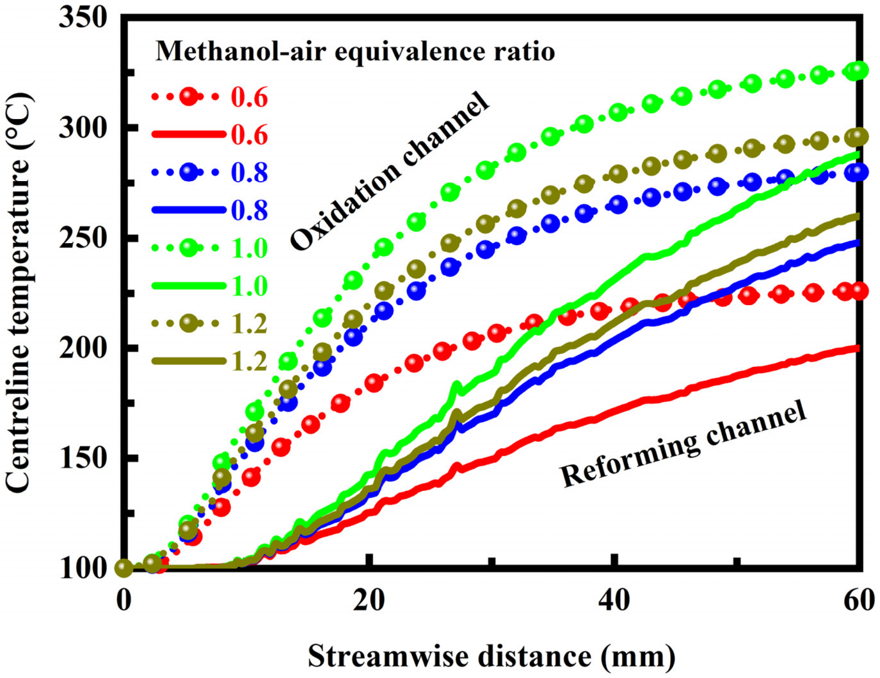


Figure 5. Effect of methanol-air equivalence ratio on the temperature along the centreline of the oxidation or reforming channel.

The results of methanol conversion and hydrogen productivity are presented in Figure 6 at different equivalence ratios of methanol to air. Methanol can be effectively converted in the reactor to hydrogen at equivalence ratios greater than 0.6. The conversion and productivity increase with the equivalence ratio. Under stoichiometric or substantially stoichiometric oxidation conditions, several advantages are realized. A high degree of completion of the endothermic reforming reaction can be achieved, and the products from the chemical process contain a high concentration of hydrogen. However, both methanol conversion and hydrogen productivity are decreased, if the fuel-air mixture has an equivalence ratio greater than one. For such fuels, high conversion and productivity levels are still possible with the endothermic reforming process. However, excess fuel is typically undesirable [51, 52] and will thus be avoided. Less methanol may be necessary to achieve the same level of conversion and productivity without the need for increasing the cost of hydrogen production. However, the presence of excess air makes the efficient production of hydrogen-rich gas much more difficult, as lower equivalence ratios decrease the methanol conversion and hydrogen productivity of the reactor with unduly compromising the efficiency of the endothermic reforming process.

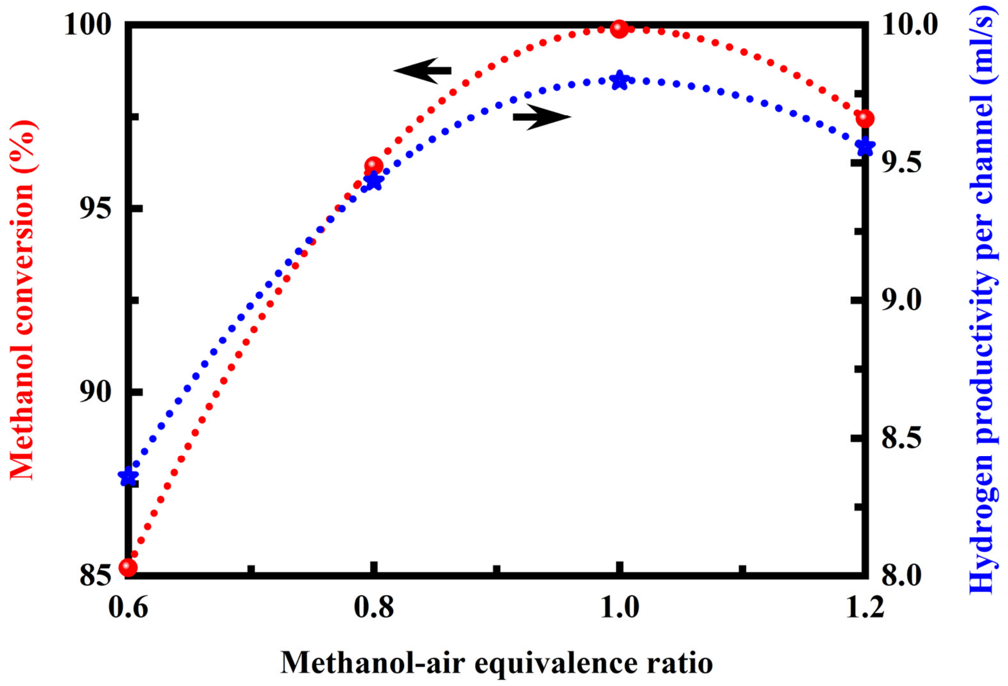
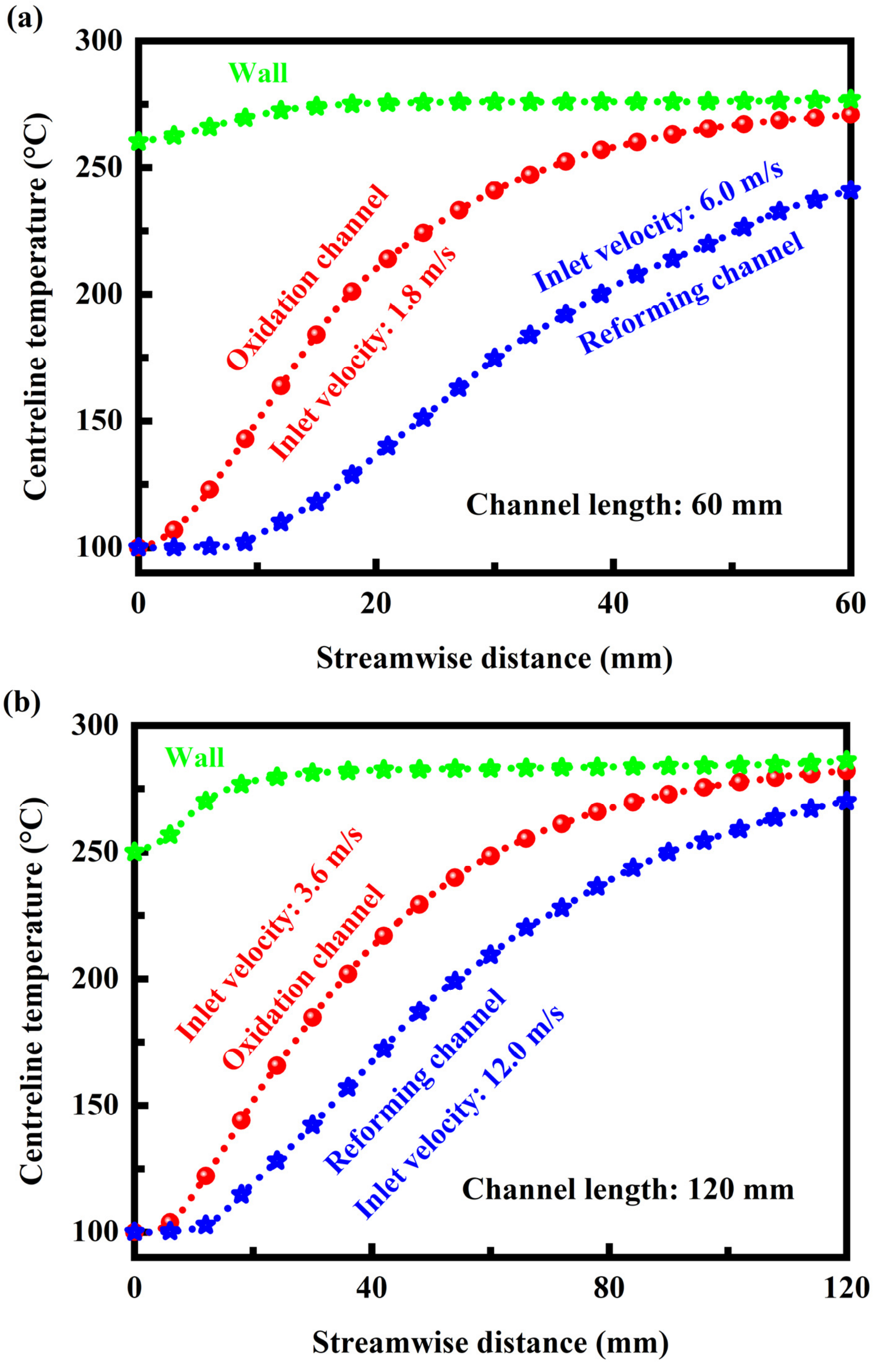


Figure 6. Effect of methanol-air equivalence ratio on the methanol conversion and the hydrogen productivity per channel.

3.2. Effect of channel length

Steam reforming of hydrocarbons is an endothermic reaction of considerable interest for hydrogen production as a fuel for fuel cells. Steam reforming produces hydrogen and carbon monoxide when heat is added to a catalytic reactor containing steam and hydrocarbons. Although exothermic and endothermic reactions are easy to implement, to do so with a compact and simple reactor design is challenging due to the limitations of heat transfer between the steam reforming reaction and the outside of the reactor. One aspect in building compact reactors with adequate thermal exchange requires a provision for high interfacial area between the reaction stream and the reactor body. Microchannel technology is capable of high heat and mass transfer coefficients between a bulk reaction fluid and the catalytic heat exchange surface. Alternating channel parallel plate designs have found application for thermally coupling endothermic steam reforming with exothermic combustion in neighbouring channels. Such designs enable orders of magnitude size reduction over conventional shell-and-tube steam reformers. Parallel flow channels are typically formed by stacking plates separated by spacers, and fitting the stack with appropriate headers so that alternating channels contain the reforming reaction with exothermic combustion in the intermediate channels.

The temperature profiles along the centreline of the channel or the wall are presented in Figure 7 at different channel lengths. As the change length is changed, the number of protrusions is adjusted while maintaining their spacing. The inlet velocities are adjusted to correspond with the channel length. More specifically, the channel length does vary substantially while maintaining a substantially constant residence time of the gas stream that remains within the reactor, which can be made by adjustments to the inlet velocity. As the channel length increases while the residence time remains substantially constant, the temperature profile along the centreline of the oxidation channel or the wall does not vary substantially. However, there are differences in centreline temperature between the reforming channels. The temperature along the reforming channel centreline increases with the channel length, as faster flows associated with long channels allow larger inner heat transfer coefficients, which improves the thermal effectiveness of the reactor but will lead to undesirably high pressure drops [57, 58] and associated operation costs. The design associated with short channels limits heat transfer between the reactants stream and the wall across the washcoat coating such that the temperature of the reformed gas leaving the reactor is less than that of such gas leaving the elongated reactor. Especially if, as may be preferred, the channel is short, the wall is nearly isothermal. As the channel length increases, the wall temperature difference becomes remarkable in the streamwise direction. The maximum temperature of the reactor increases with the channel length. The inlet velocities must be closely adjusted by varying the flow rates in order to limit the maximum temperature, as a variation in the temperature outside the range from 200 °C to 300 °C may cause undesired side reactions to occur within the reactor. Accordingly, the velocity of flow of the reactants must be sufficiently high to absorb the heat flux across the wall. Long channels can be used to reduce the difference in gas exit temperature between the oxidation and reforming channels while maintaining a substantially constant residence time of the process flow stream. There is no significant difference in gas exit temperature between the channels if the reactor is sufficiently long.



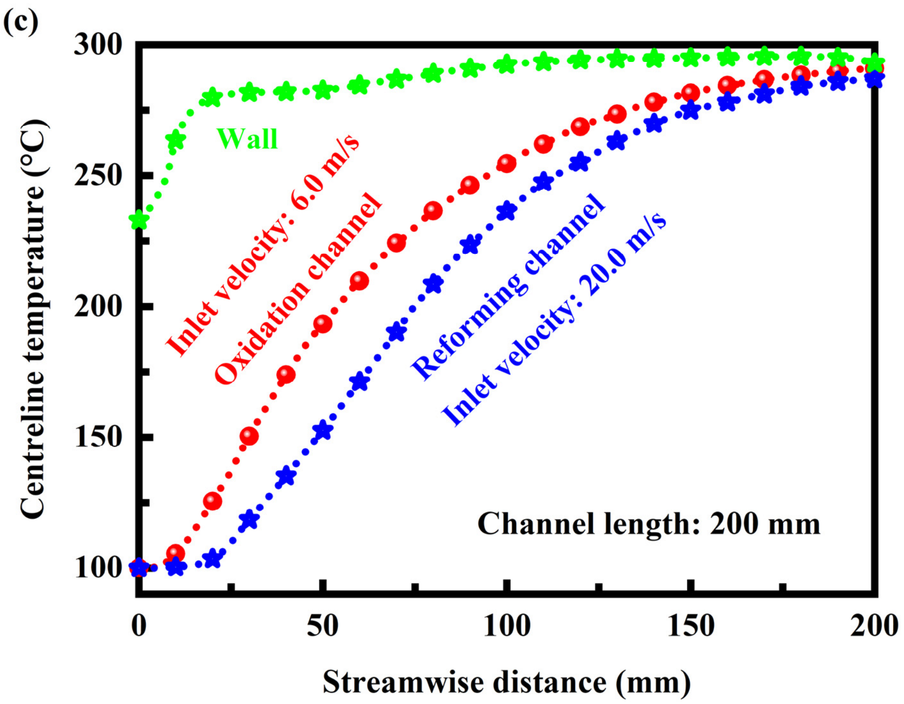


Figure 7. (a) Temperature profiles along the centreline of the channel or the wall in the case that the channel is short. (b) Temperature profiles along the centreline of the channel or the wall in the case that the channel is of moderate length. (c) Temperature profiles along the centreline of the channel or the wall in the case that the channel is long.

The results of methanol conversion and hydrogen productivity are presented in Figure 8 at different channel lengths, wherein the hydrogen productivity is calculated per channel. The channels must be of sufficient length to allow the endothermic reforming reaction to proceed to the required conversion level. Interestingly, the methanol conversion does not vary substantially as the channel length increases in the range from about 88 percent to about 92 percent. Consequently, the use of short channels has cost advantages for small-scale applications. In contrast, the use of long channels will lead to undesirably high pressure drops through the channels [57, 58]. The short-channel design may be preferred over the long-channel design in order to simultaneously achieve low pressure drops and sufficiently high conversions in the reactor. Accordingly, the overall reactor length can be reduced to obtain the desired conversion. However, there is significant difference in hydrogen productivity between the channels due to changes in the flow rate of the process flow stream. Long channels can be used in favour of hydrogen production, as the rate of flow of the mixture undergoing steam reforming is increased without adversely affecting the conversion. For example, the use of the longest channels allows at least a three-fold increase in hydrogen productivity. For the use of long channels, there is a trade-off between the benefits of improved productivity and the disadvantages of high pressure drops. Expectable compromises have to be made between hydrogen productivity and pressure drop. Consequently, a protruded design that can minimize pressure drop whilst promoting productivity levels is desired. The reactor design suffers from a fundamental limitation resulting from the flow configuration in which a reacting stream flows parallel to a heat transfer surface through which the majority of heat is transferred perpendicular to the direction of fluid flow. Regardless of the reaction taking place in the reaction channels, its reaction rate will vary along the flow length of that channel due to changes in concentration and temperature. Balancing the heat requirements of an endothermic reaction with heat generated by an exothermic reaction flowing parallel to and on the opposite side of the wall is extraordinarily difficult since the endothermic reaction has a very different dependence upon concentration and temperature than the endothermic reaction. Along the flow length of the wall that divides these reactions, the heat flux through the wall that is perpendicular to fluid flow will vary due to temperature and reaction rate differences along the flow length of the wall. Since the thermally coupled reactions are so closely coupled, neither reaction can run at a significantly different reaction rate at any point along the channel length. Thus, each reaction will exhibit a peak in reaction rate at nearly the same position within the reactor with slower reaction rates before and after this peak, which leads to the need for a long reactor channel to ensure complete conversion. A specific example of this reaction rate problem encountered in the parallel flow arrangement is demonstrated by attempts to drive endothermic steam reforming with exothermic combustion in alternating parallel channel reactors. A convenient way to supply heat is to couple the endothermic reaction with an exothermic combustion reaction in the heat exchange channels. Consequently, the stacked reactor becomes an alternating series of endothermic and exothermic reactors separated by thin heat exchange walls. Unfortunately, the combustion reaction is difficult to control with convenient combustion catalysts and fuels, and most of the combustion occurs near the fuel inlet. This uneven combustion results in uneven heat transfer to the endothermic reaction and poor overall reactor performance.

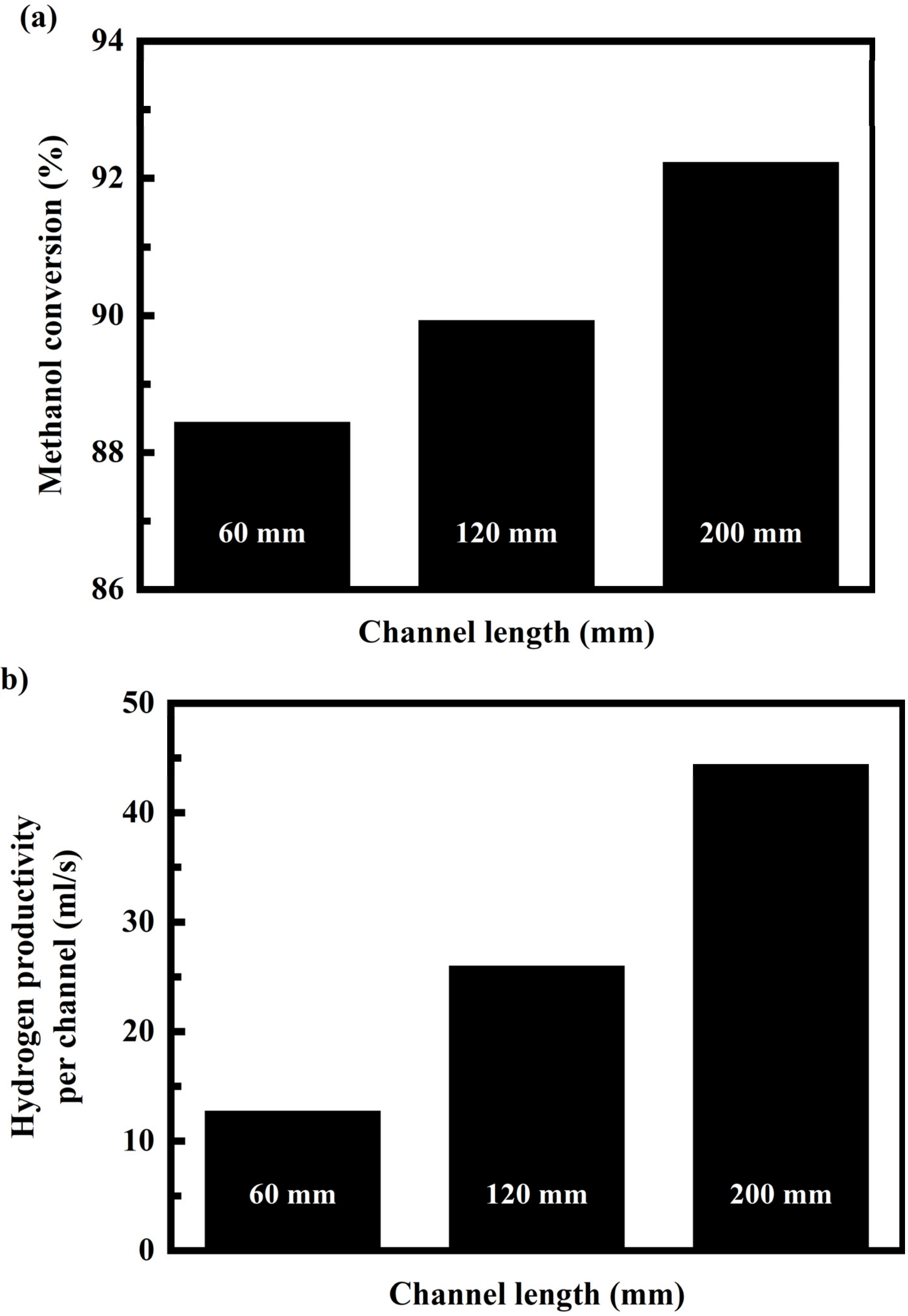


Figure 8. (a) Effect of the length of the channel on the methanol conversion of the reactor. (b) Effect of the length of the channel on the hydrogen productivity per channel.

4. Conclusions

Computational fluid dynamics was used to delineate the role of methanol-air equivalence ratio and channel length in the performance of a protruded millisecond microchannel reactor, wherein a steam reforming reaction is proceeding and protrusions are used to improve the transport processes involved. Recommendations are made on how to optimize design for better reactor performance. Account is taken of the factors that may influence the performance of the protruded reactor. The conclusions are summarized primarily as follows:

- The equivalence ratio and channel length must be closely adjusted to satisfy the reaction conditions in practice, thereby ensuring efficient operation of the reactor.
- Necessary adjustments to the equivalence ratio of methanol to air can be made to control the maximum reactor temperature within certain needed limits.
- Under stoichiometric or substantially stoichiometric oxidation conditions, a high degree of completion of the endothermic reforming reaction can be achieved, and the products from the chemical process contain a high concentration of hydrogen.
- The channels must be of sufficient length to allow the endothermic reforming reaction to proceed to the required conversion level.
- The short-channel design may be preferred over the long-channel design in order to simultaneously achieve low pressure drops and sufficiently high conversions in the reactor.
- Expectable compromises have to be made between hydrogen productivity and pressure drop. A protruded design that can minimize pressure drop whilst promoting productivity levels is desired.

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