WITHDRAWN: Computational study of flame characteristics and stability of a methane-air mixture in a cavity-stabilized burner for portable power applications

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Research Article

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EDITORIAL NOTE:

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Abstract

Flame propagation in microchannels is modeled using two-dimensional computational fluid dynamics simulations with detailed multicomponent transport, gas-phase chemistry, heat loss through the wall, radical recombination at walls, and possible temperature discontinuity at the wall due to lack of thermal accommodation. Numerical simulations are conducted to gain insights into burner performance such as temperatures, reaction rates, and flames. The effects of inlet velocity, wall thermal conductivity, and heat transfer coefficient on flame stability are investigated. The factors affecting combustion characteristics and flame stability are determined. Design recommendations are provided. The results indicate that under certain conditions of preheating and insulation, methane-air flames are able to propagate in micro-channels. The near-entrance heat loss and radical quenching at the wall are key issues in controlling flame propagation in micro-channels. The choice of the wall material is crucial in terms of insulating and radical quenching properties, when designing cavity-stabilized burners. The inlet velocity of the mixture is a critical factor in assuring flame stability within the cavity-stabilized burner. There is a narrow range of inlet velocities that permit sustained combustion within the cavity-stabilized burner. Fast flows can cause blowout and slow flows can cause extinction. There exists an optimum inlet velocity for greatest flame stability. The thermal conductivity of the burner walls plays a vital role in flame stability. Improvements in flame stability are achievable by using walls with anisotropic thermal conductivity. Heat-insulating materials are favored to minimize external heat losses.

1. Introduction

Micro-burners are increasingly studied for the catalytic and non-catalytic portable production of heat and energy [1, 2]. The energy produced can be utilized by thermos-electrics to generate electric power or via endothermic reactions, such as ammonia decomposition and steam reforming, to produce hydrogen for fuel cells [3, 4]. Hydrocarbons contain a significantly larger energy density than traditional lithium batteries, rendering possible the production of long-lasting and lighter devices for a number of applications such as telecommunications, unmanned compact military aircraft, cell phones, and laptops [5, 6]. Furthermore, devices that are powered by hydrocarbons can be easily refilled by adding fuel, whereas batteries can require a lengthy time and specialized equipment for recharging [7, 8]. This consideration is especially important for military applications.

One approach for creating micro-combustors is to simply miniaturize conventional large-scale combustion devices [9, 10]. Gas-phase combustion provides a high volumetric heat release as compared to catalytic combustion, which is slowed by mass-transfer limitations. However, flames are typically extinguished when confined in gaps of less than one millimeter because of thermal and radical quenching at walls [11, 12]. These quenching mechanisms become more pronounced as the surface-to-volume ratio increases in devices of one millimeter gap size or below.

Because of the importance of power generation at the microscale [1, 2], several groups have recently revisited the development of homogeneous micro-combustion devices [3, 4]. Micro-burners have been developed to allow self-sustained homogeneous combustion in channels with gaps of less than one millimeter [13, 14]. This important achievement was accomplished by using components fabricated from alumina that were modified to reduce radical adsorption and insulated to reduce thermal losses [15, 16]. Specifically, radical trapping sites were eliminated by annealing at high temperatures and cleaning the surface to remove heavy metals. These burners have been shown to successfully combust methane-oxygen mixtures.

In parallel with experimental efforts, simulations have been performed using detailed gas and surface chemistry under the boundary-layer approximation or one-step chemistry in full, two-dimensional computational fluid dynamics models to study the role of different fuels, materials of construction, heat losses, and radical quenching in the flame stability of homogeneous micro-burners [17, 18]. These studies have shown that the reactor walls provide upstream heat transfer that preheats the cold, incoming feed, as well as transverse heat losses to the surroundings [17, 18]. This mechanistic tradeoff leads to a narrow range of construction materials that conduct sufficient heat to ignite the feed, yet are insulating enough to minimize external heat losses. Even when the wall materials are optimized, the allowable heat losses are generally very low, so that the flow is restricted to a relatively narrow window of operation [19, 20]. Finally, wall temperatures in gaseous micro-burners often exceed 1500 K and can reach adiabatic flame temperatures. Such high temperatures greatly limit the available materials of construction, result in nitrogen oxides production, and require considerable device insulation and packaging [21, 22]. Although temperature reduction is possible by shrinking the device size, self-sustained oscillations in temperature and pressure emerge, leading eventually to mechanical device failure [23, 24]. If gaseous micro-burners are to be used for the production of energy in direct contact with reactors containing endothermic reactions, the stability of the micro-flames must be robust enough to withstand substantial heat harvesting [25, 26]. This currently appears to be a challenging undertaking. A fundamental understanding of the stabilization mechanisms of a flame within very small spaces by the cavity method is of both fundamental and practical significance. However, the precise mechanism by which the cavity method generally provides increased flame stability remains unclear and warrants further study.

This study relates to the combustion characteristics of a micro-structured cavity-stabilized burner. Numerical simulations are conducted to gain insights into burner performance such as temperatures, reaction rates, and flames. The effects of wall thermal conductivity, inlet velocity, and heat transfer coefficient on flame stability are investigated. The factors affecting combustion characteristics are determined for the cavity-stabilized burner. Particular focus is placed on determining essential factors that affect the performance of the burner.

2. Computational Methods

The use of a cavity configuration is particularly advantageous when arranged as a disturbance factor for a millimeter-scale burner. The millimeter-scale burner designed with cavities is depicted schematically in Fig. 1. A lean methane-air mixture is conducted through a combustion chamber defined by parallel plates. The length of the channel is 50 mm, the height is 3 mm, and the width is 13 mm. A sudden cross section change of the axial flow cross section is present along the length of the burner. The depth of the cavities is 1.5 mm, the width of the cavities is 4 mm, and the distance away from the entrance is 10 mm. The angle of the cavity is 45°, and the thickness of the plates is 3 mm, as depicted schematically in Fig. 1. The initial temperature is 1500 K, with a Reynolds number greater than 500 at the inlet. Due to the small internal space of the burner, the gas flow rate is small. Therefore, gas radiation and volume force are ignored in the model.

Numerical simulations are conducted using computational fluid dynamics to gain insights into burner performance such as reaction rates, temperatures, and flames. Computational fluid dynamics is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows. Computers are used to perform the computations required to simulate the free-stream flow of the fluid, and the interaction of the fluid with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved, and are often required to solve the largest and most complex problems. Ongoing research yields software that improves the accuracy and speed of complex simulation scenarios. In addition, previously performed analytical or empirical analysis of a particular problem can be used for comparison. A final validation is often performed using full-scale testing. The length scale of the burner is 3 mm for the combustion problem. In all the cases studied, the Reynolds number is less than 1270 due to the very small scale of the system, causing the gases to flow into the chamber in a laminar flow regime. The mathematical model is solved and implemented in ANSYS FLUENT to obtain the problem solution. ANSYS FLUENT permits multi-dimensional modeling of physical and chemical phenomena in the processes [27, 28], and various modes of heat transfer can be modeled.

The laminar finite-rate model computes the chemical source terms using Arrhenius expressions, and ignores the effects of turbulent fluctuations. The model is exact for laminar flames, but is generally inaccurate for turbulent flames due to highly non-linear Arrhenius chemical kinetics. In the present study, the gases flow through the channel in a laminar flow regime, as noted above. Therefore, the laminar finite-rate model [29] is used to compute the chemical source terms. This chemical kinetic model can be used to accurately describe flame dynamics and flame responses to external perturbations [30]. Thermal effects can be relatively well captured by the chemical kinetic model.

Successful computations of turbulent flows require some consideration during the mesh generation. Turbulent flow is often wall-bounded and the wall affects the flow significantly [31]. Consequently, the numerical results for turbulent flows tend to be more susceptible to mesh dependency than those for laminar flows. Accordingly, different strategies must be used in the vicinity of the wall depending on the chosen near-wall meshing [32]. In the present study, however, the gases flow through the channel in a laminar flow regime, as noted above. In laminar flows, wall boundary conditions are used to bound fluid and solid regions and the no-slip boundary condition is enforced at walls. In fluid dynamics, laminar flow is characterized by fluid particles following smooth paths in layers, with each layer moving smoothly past the adjacent layers with little or no mixing. At low velocities, the fluid tends to flow without lateral mixing, and adjacent layers slide past one another like playing cards. There are no cross-currents perpendicular to the direction of flow, nor eddies or swirls of fluids. In laminar flow, the motion of the particles of the fluid is very orderly with particles close to a solid surface moving in straight lines parallel to that surface. Laminar flow is a flow regime characterized by high momentum diffusion and low momentum convection. Laminar flow occurs at lower velocities, below a threshold at which the flow becomes turbulent.

To verify the accuracy of the model, the predictions are compared with the data obtained from experimental measurements. The burner comprises two parallel fused-quartz plates. An ordinary camera is used to form an image using visible light, and a thermographic camera is used to create an image using infrared radiation. The thermographic camera can achieve a resolution of 640 × 480 pixels, and a temperature difference of 1.0 K at the scene induces a maximum temperature difference of 0.02 K at the sensor. The stable fluid centerline temperature profiles are determined from thermographic measurements using infrared radiation. A constant fuel-air stoichiometry is maintained in operation. The contour plot of temperature in the burner is presented in Fig. 2. The thermographic image acquired in the infrared spectral region is also presented in Fig. 2. The fluid centerline temperature profiles are determined from thermographic measurements and predicted by the model. The predictions are in satisfactory agreement with the data obtained from experimental measurements.

3. Results And Discussion

The results obtained for the critical external heat loss coefficient as a function of wall thermal conductivity are presented in Fig. 3. These bell-shaped envelopes separate the region of self-sustained combustion below the curve from the region above the curve where combustion cannot be self-sustained. There exists a critical wall thermal conductivity for the mixture, below which combustion cannot be self-sustained, even with insulating walls, as presented in Fig. 3. When the wall thermal conductivity increases from low values, the allowable-heat-loss coefficient first increases quickly, and then decreases and levels off in the range of metals or high-thermal-conductivity ceramics, for example, silicon carbide. The allowable-heat-loss coefficient reaches a maximum for insulating ceramics such as silica and alumina. The behavior obtained for low-conductivity materials is at first counterintuitive. Highly insulating materials are poor for flame stability due to the lack of a continuous ignition source, needed to preheat the cold incoming gases.

The effect of inlet velocity on the flame location in micro-burners is illustrated in Fig. 4. As the inlet velocity increases from moderate values, the convective timescale decreases, and a shift in the flame location downstream is observed, as expected. At sufficiently high flow velocities, blowout occurs, as illustrated in Fig. 4. This behavior is consistent with parabolic boundary layer approximation flow simulations [18]. However, in contrast to parabolic boundary layer approximation simulations [18], a non-linear relationship is observed for relatively slow flows. In particular, for sufficiently low inlet velocities, the flame location increases again significantly as the inlet velocity decreases, resulting in extinction.

The transverse rate profiles of the combustion reaction are presented in Fig. 5 at different distances from the axial centerline. The velocity is 0.3 m/s. When the distance from the axial centerline is 0.5 mm and 1.0 mm, the peak of the reaction rate generally occurs near the middle of the cavity-stabilized burner. When the position is near the inner wall surface, the peak of the reaction rate is close to the entrance, as presented in Fig. 5. This is because when the velocity is low, the wall temperature is higher than the temperature of the central flow channel, and the gas near the wall can quickly absorb heat and reach the ignition temperature to react. The irregular change of the rate of the combustion reaction near the cavities is mainly due to the formation of low-speed recirculation regions, in which the heat and mass transfer in the cavities are uneven. Advantageously, the recirculation regions make the gas in the cavities flow violently, which facilitates the combustion process.

The contour plots of temperature are presented in Fig. 6 at different thermal conductivities. The thermal conductivity of the solid material has little effect on the temperature of the fluid but has a strong effect on the temperature of the walls. The temperature gradient is steep within the walls with a low thermal conductivity. The temperature of the exterior walls typically increases with the thermal conductivity. The solid material is advantageously thermally conductive to permit a high wall temperature with more uniform distribution. A portion of heat of reaction is transferred to the upstream structure of the burner by heat conduction through the walls, which is necessary for ignition and flame stability [33, 34]. The term anisotropy is used in Fig. 6 to describe direction-dependent thermal conductivity of the solid material. In this case, the anisotropic solid material inhibits transverse but allows longitudinal heat conduction. The walls permit heat flux in the longitudinal direction to preheat the fluid [35, 36], yet does not permit heat losses in the transverse direction to the surroundings. It is important to delineate the thermal versus kinetic contributions of radical quenching on flame propagation in micro-channels [37, 38]. The energy boundary condition at the surface should then take into account heat loss through the wall of the micro-channel and the possible temperature discontinuity at the wall. Detailed mathematical modeling is invaluable in elucidating the mechanisms of combustion and assisting in the design of high-temperature micro-chemical systems. Finally, there are other factors that are important to the design of optimum micro-combustors that have not been discussed here. The first is the conductance, the product of the thermal conductivity and the cross-sectional area, which limits upstream heat conduction through the structure. Making this parameter very large would increase the power density at the optimum until a limit imposed by the heat transfer coefficient between the gas and the structure is reached. The second factor is the pressure drop which is a very important consideration when integrating a combustor into a power cycle. Combustors designed to be at or near the optimum power density configuration could be integrated into practical power systems.

4. Conclusions

Numerical simulations are conducted using computational fluid dynamics to gain insights into burner performance such as reaction rates, temperatures, and flames. The factors affecting combustion characteristics are determined for the cavity-stabilized burner.

The results indicate that there are important competitions between heat loss, radical quenching, and heat generation. Methane-air flames are able to propagate in micro-channels under certain conditions of preheating and insulation. The inlet velocity of the mixture is a critical factor in assuring flame stability within the cavity-stabilized burner. There is a narrow range of inlet velocities that permit sustained combustion within the cavity-stabilized burner. The thermal conductivity of the burner walls plays a vital role in flame stability. Burner walls with low thermal conductivity will cause hot spots, and burner walls with high thermal conductivity are substantially isothermal. Improvements in flame stability are achievable by using walls with anisotropic thermal conductivity. Such walls with anisotropic heat conduction properties will allow upstream heat flux to preheat the incoming admixture of gases, yet not allow heat losses in the transverse direction. Loss of flame stability due to external heat losses are main issues that require thermal management. The near-entrance heat loss and radical quenching at the wall are key issues in controlling flame propagation in micro-channels. The choice of the wall material is crucial in terms of insulating and radical quenching properties, when designing cavity-stabilized burners. Heat-insulating materials are favored to minimize external heat losses.

Declarations

Declaration of competing interest

The authors declare that there is no conflict of interest.

References

1. Y. Ju and K. Maruta. Microscale combustion: Technology development and fundamental research. Progress in Energy and Combustion Science, Volume 37, Issue 6, 2011, Pages 669–715.
2. S.K. Chou, W.M. Yang, K.J. Chua, J. Li, and K.L. Zhang. Development of micro power generators - A review. Applied Energy, Volume 88, Issue 1, 2011, Pages 1–16.
3. D.C. Walther and J. Ahn. Advances and challenges in the development of power-generation systems at small scales. Progress in Energy and Combustion Science, Volume 37, Issue 5, 2011, Pages 583–610.
4. N.S. Kaisare and D.G. Vlachos. A review on microcombustion: Fundamentals, devices and applications. Progress in Energy and Combustion Science, Volume 38, Issue 3, 2012, Pages 321–359.
5. D. Dunn-Rankin, E.M. Leal, and D.C. Walther. Personal power systems. *Progress in Energy and Combustion Science*, Volume 31, Issues 5–6, 2005, Pages 422–465.
6. J. E, J. Ding, J. Chen, G. Liao, F. Zhang, and B. Luo. Process in micro-combustion and energy conversion of micro power system: A review. *Energy Conversion and Management*, Volume 246, 2021, Article Number: 114664.
7. J. E, B. Luo, D. Han, J. Chen, G. Liao, F. Zhang, and J. Ding. A comprehensive review on performance improvement of micro energy mechanical system: Heat transfer, micro combustion and energy

conversion. Energy, Volume 239, Part E, 2022, Article Number: 122509.

8. A.C. Fernandez-Pello. Micropower generation using combustion: Issues and approaches. *Proceedings of the Combustion Institute*, Volume 29, Issue 1, 2002, Pages 883–899.
9. D.G. Norton and D.G. Vlachos. Combustion characteristics and flame stability at the microscale: a CFD study of premixed methane-air mixtures. Chemical Engineering Science, Volume 58, Issue 21, 2003, Pages 4871–4882.
10. D.G. Norton and D.G. Vlachos. A CFD study of propane-air microflame stability. *Combustion and Flame*, Volume 138, Issues 1–2, 2004, Pages 97–107.
11. C.-H. Chen and P.D. Ronney. Scale and geometry effects on heat-recirculating combustors. Combustion Theory and Modelling, Volume 17, Issue 5, 2013, Pages 888–905.
12. N.S. Kaisare and D.G. Vlachos. Optimal reactor dimensions for homogeneous combustion in small channels. Catalysis Today, Volume 120, Issue 1, 2007, Pages 96–106.
13. C.M. Miesse, R.I. Masel, C.D. Jensen, M.A. Shannon, and M. Short. Submillimeter-scale combustion. AIChE Journal, Volume 50, Issue 12, 2004, Pages 3206–3214.
14. C. Miesse, R.I. Masel, M. Short, and M.A. Shannon. Diffusion flame instabilities in a 0.75mm non-premixed microburner. *Proceedings of the Combustion Institute*, Volume 30, Issue 2, 2005, Pages 2499–2507.
15. C. Miesse, R.I. Masel, M. Short, and M.A. Shannon. Experimental observations of methane-oxygen diffusion flame structure in a sub-millimetre microburner. Combustion Theory and Modelling, Volume 9, Issue 1, 2005, Pages 77–92.
16. S. Prakash, A.D. Armijo, R.I. Masel, and M.A. Shannon. Flame dynamics and structure within sub-millimeter combustors. AIChE Journal, Volume 53, Issue 6, 2007, Pages 1568–1577.
17. D.G. Norton, E.D. Wetzel, and D.G. Vlachos. Fabrication of single-channel catalytic microburners: Effect of confinement on the oxidation of hydrogen-air mixtures. Industrial & Engineering Chemistry Research, Volume 43, Issue 16, 2004, Pages 4833–4840.
18. S. Raimondeau, D. Norton, D.G. Vlachos, and R.I. Masel. Modeling of high-temperature microburners. *Proceedings of the Combustion Institute*, Volume 29, Issue 1, 2002, Pages 901–907.
19. T.T. Leach and C.P. Cadou. The role of structural heat exchange and heat loss in the design of efficient silicon micro-combustors. *Proceedings of the Combustion Institute*, Volume 30, Issue 2, 2005, Pages 2437–2444.
20. T.T. Leach, C.P. Cadou, and G.S. Jackson. Effect of structural conduction and heat loss on combustion in micro-channels. Combustion Theory and Modelling, Volume 10, Issue 1, 2006, Pages 85–103.
21. C.C. Rasmussen, J.F. Driscoll, K.-Y. Hsu, J.M. Donbar, M.R. Gruber, and C.D. Carter. Stability limits of cavity-stabilized flames in supersonic flow. *Proceedings of the Combustion Institute*, Volume 30, Issue 2, 2005, Pages 2825–2833.

22. N. Kato and S.-K. Im. Flame dynamics under various backpressures in a model scramjet with and without a cavity flameholder. *Proceedings of the Combustion Institute*, Volume 38, Issue 3, 2021, Pages 3861–3868.
23. S.J. Shanbhogue, S. Husain, and T. Lieuwen. Lean blowoff of bluff body stabilized flames: Scaling and dynamics. Progress in Energy and Combustion Science, Volume 35, Issue 1, 2009, Pages 98–120.
24. J. Choi, W. Lee, R. Rajasegar, T. Lee, and J. Yoo. Effects of hydrogen enhancement on mesoscale burner array flame stability under acoustic perturbations. International Journal of Hydrogen Energy, Volume 46, Issue 74, 2021, Pages 37098–37107.
25. J.A. Federici, E.D. Wetzel, B.R. Geil, and D.G. Vlachos. Single channel and heat recirculation catalytic microburners: An experimental and computational fluid dynamics study. *Proceedings of the Combustion Institute*, Volume 32, Issue 2, 2009, Pages 3011–3018.
26. N.S. Kaisare, S.R. Deshmukh, and D.G. Vlachos. Stability and performance of catalytic microreactors: Simulations of propane catalytic combustion on Pt. Chemical Engineering Science, Volume 63, Issue 4, 2008, Pages 1098–1116.
27. S. Wang and A. Fan. Combustion regimes of syngas flame in a micro flow reactor with controlled temperature profile: A numerical study. *Combustion and Flame*, Volume 230, 2021, Article Number: 111457.
28. S. Ni, D. Zhao, Y. You, Y. Huang, B. Wang, and Y. Su. NOx emission and energy conversion efficiency studies on ammonia-powered micro-combustor with ring-shaped ribs in fuel-rich combustion. *Journal of Cleaner Production*, Volume 320, 2021, Article Number: 128901.
29. C.K. Westbrook and F.L. Dryer. Simplified reaction mechanisms for the oxidation of hydrocarbon fuels in flames. *Combustion Science and Technology*, Volume 27, Issues 1–2, 1981, Pages 31–43.
30. C.K. Westbrook and F.L. Dryer. Chemical kinetic modeling of hydrocarbon combustion. Progress in Energy and Combustion Science, Volume 10, Issue 1, 1984, Pages 1–57.
31. J. Jiménez. Near-wall turbulence. *Physics of Fluids*, Volume 25, Issue 10, 2013, Article Number: 101302.
32. M.S. Cellek. Turbulent flames investigation of methane and syngas fuels with the perspective of near-wall treatment models. International Journal of Hydrogen Energy, Volume 45, Issue 60, 2020, Pages 35223–35234.
33. J. Choi, R. Rajasegar, W. Lee, T. Lee, and J. Yoo. Hydrogen enhancement on a mesoscale swirl stabilized burner array. International Journal of Hydrogen Energy, Volume 46, Issue 46, 2021, Pages 23906–23915.
34. M. Lee, Y. Fan, Y. Ju, and Y. Suzuki. Ignition characteristics of premixed cool flames on a heated wall. *Combustion and Flame*, Volume 231, 2021, Article Number: 111476.
35. Y. Fan, W. Lin, S. Wan, and Y. Suzuki. Investigation of wall chemical effect using PLIF measurement of OH radical generated by pulsed electric discharge. Combustion and Flame, Volume 196, 2018, Pages 255–264.

36. Y. Saiki, Y. Fan, and Y. Suzuki. Radical quenching of metal wall surface in a methane-air premixed flame. Combustion and Flame, Volume 162, Issue 10, 2015, Pages 4036–4045.
37. T.J. Poinsot, D.C. Haworth, and G. Bruneaux. Direct simulation and modeling of flame-wall interaction for premixed turbulent combustion. *Combustion and Flame*, Volume 95, Issues 1–2, 1993, Pages 118–132.
38. P. Popp and M. Baum. Analysis of wall heat fluxes, reaction mechanisms, and unburnt hydrocarbons during the head-on quenching of a laminar methane flame. Combustion and Flame, Volume 108, Issue 3, 1997, Pages 327–348.

Figures

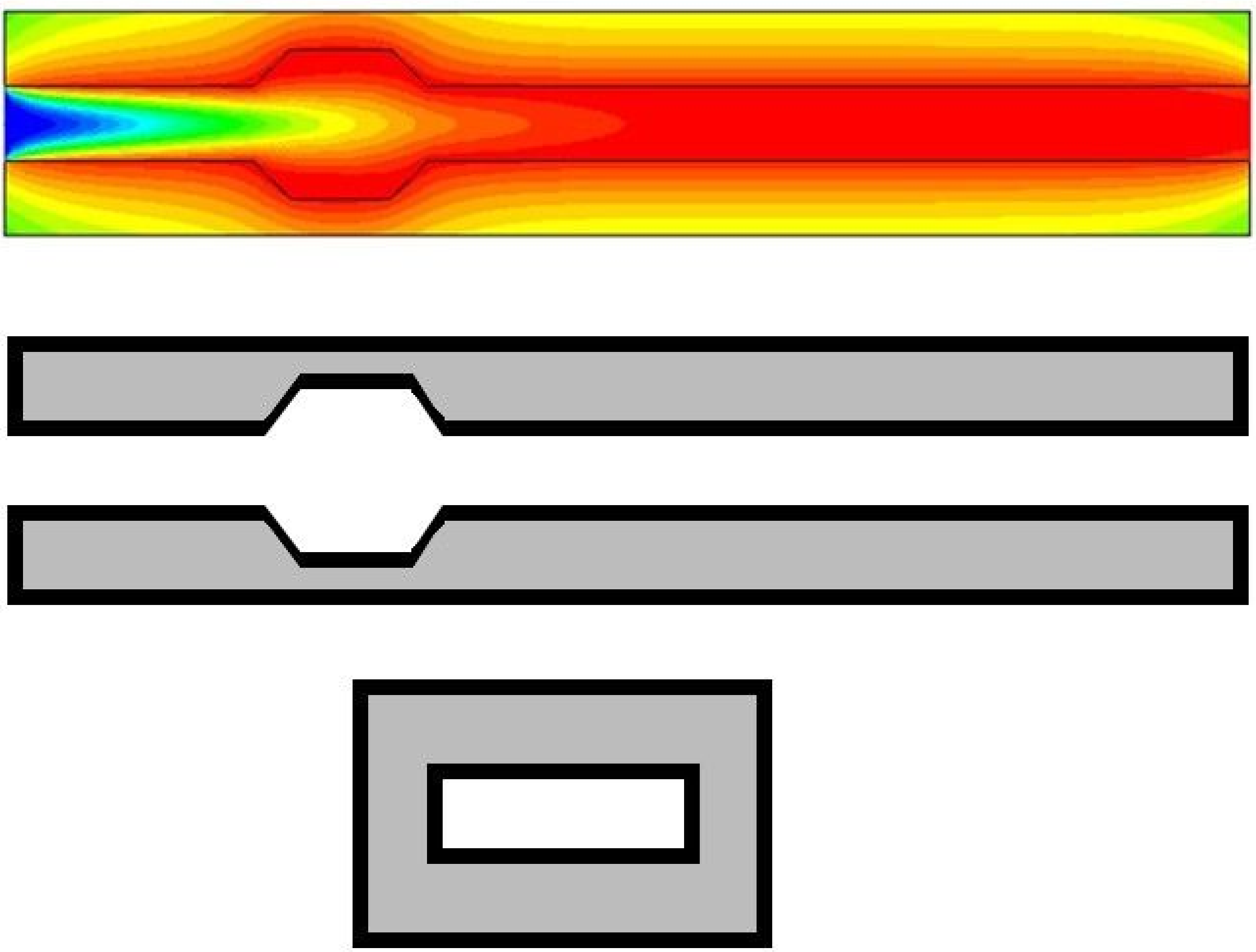

Figure 1

Schematic illustration of the millimeter-scale combustion system designed with cavities on the channel walls.

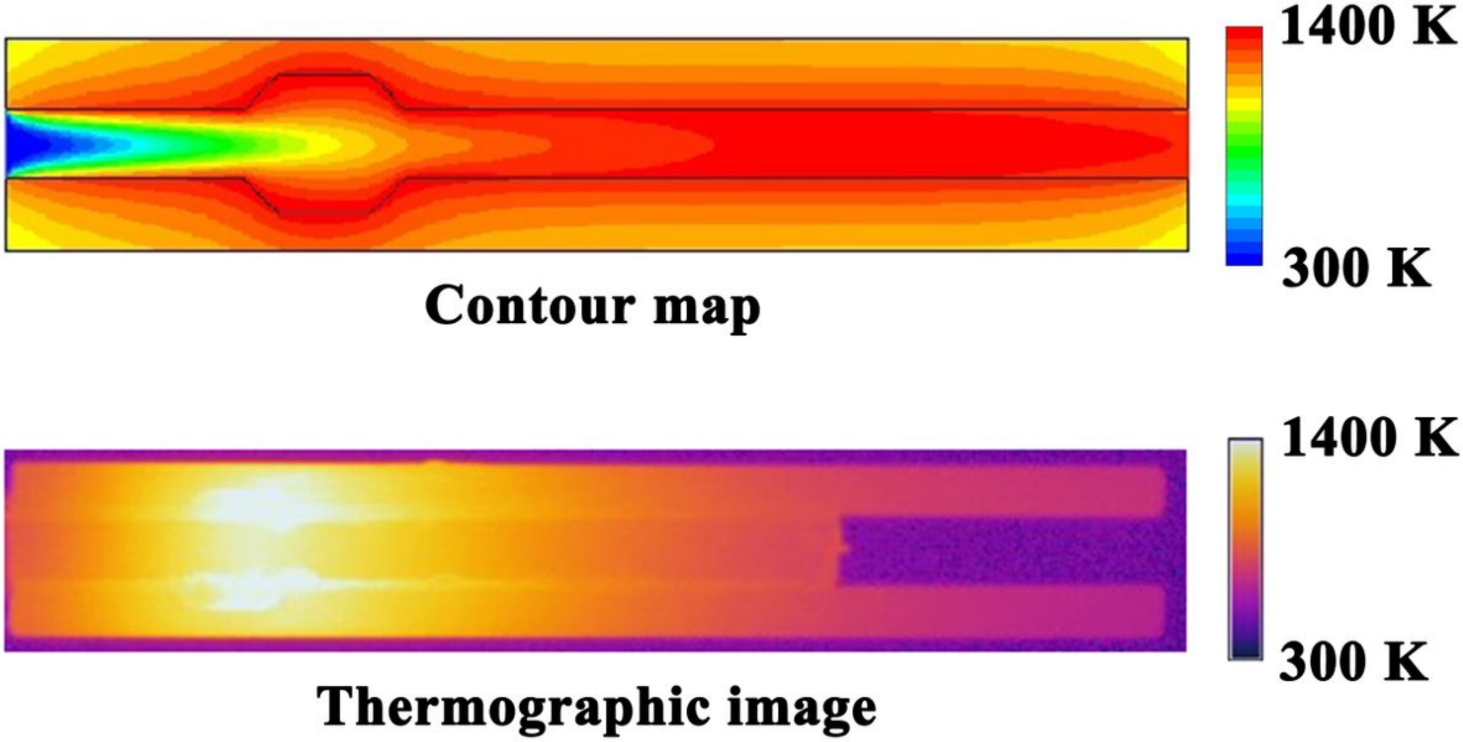

Figure 2

Laminar premixed methane flames and temperature variation in the burner. A constant fuel-air stoichiometry is maintained in operation.

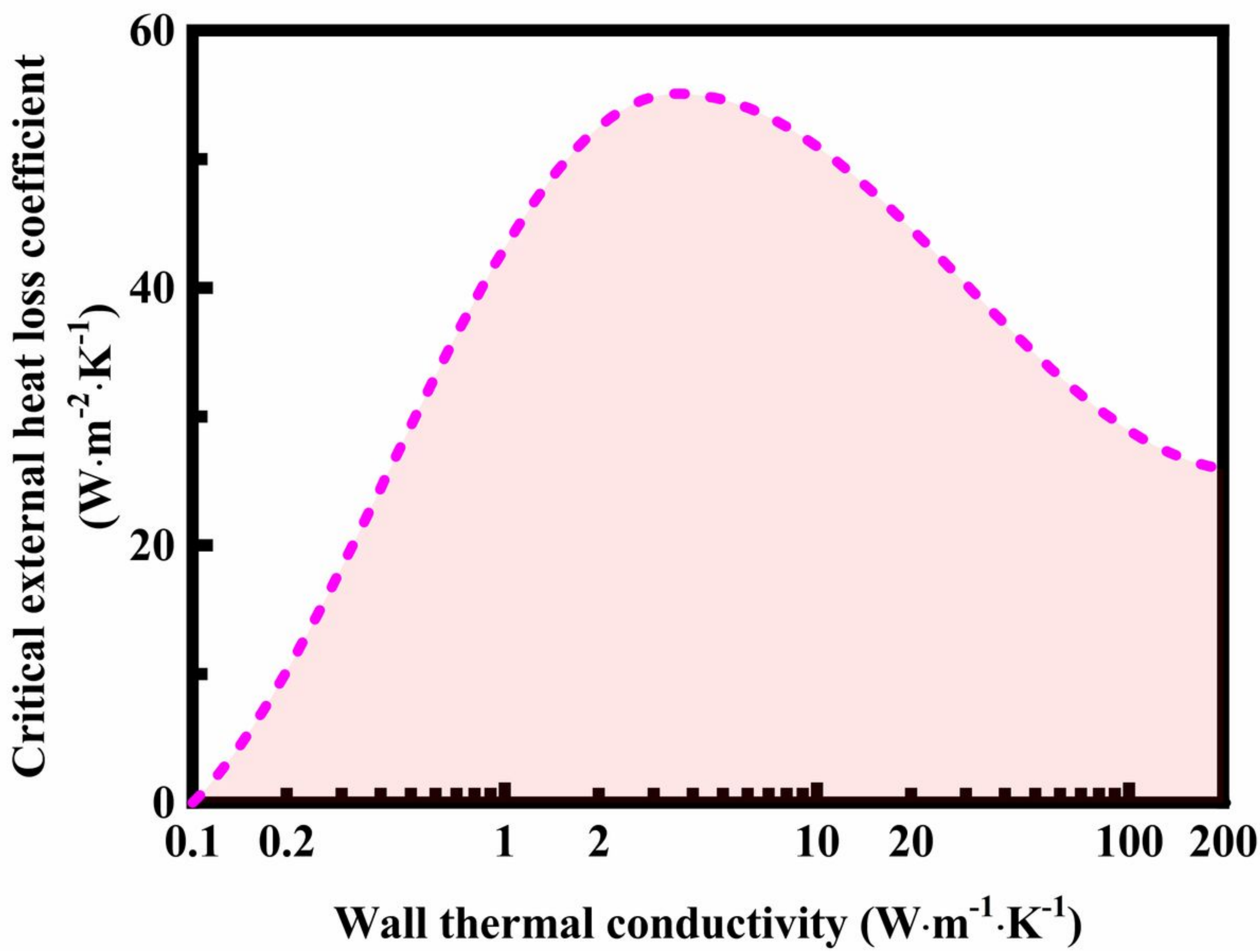

Figure 3

Critical external heat loss coefficient as a function of wall thermal conductivity. Materials with lower wall thermal conductivities limit the upstream heat transfer. Materials with higher wall thermal conductivities result in enhanced heat transfer to the surroundings.

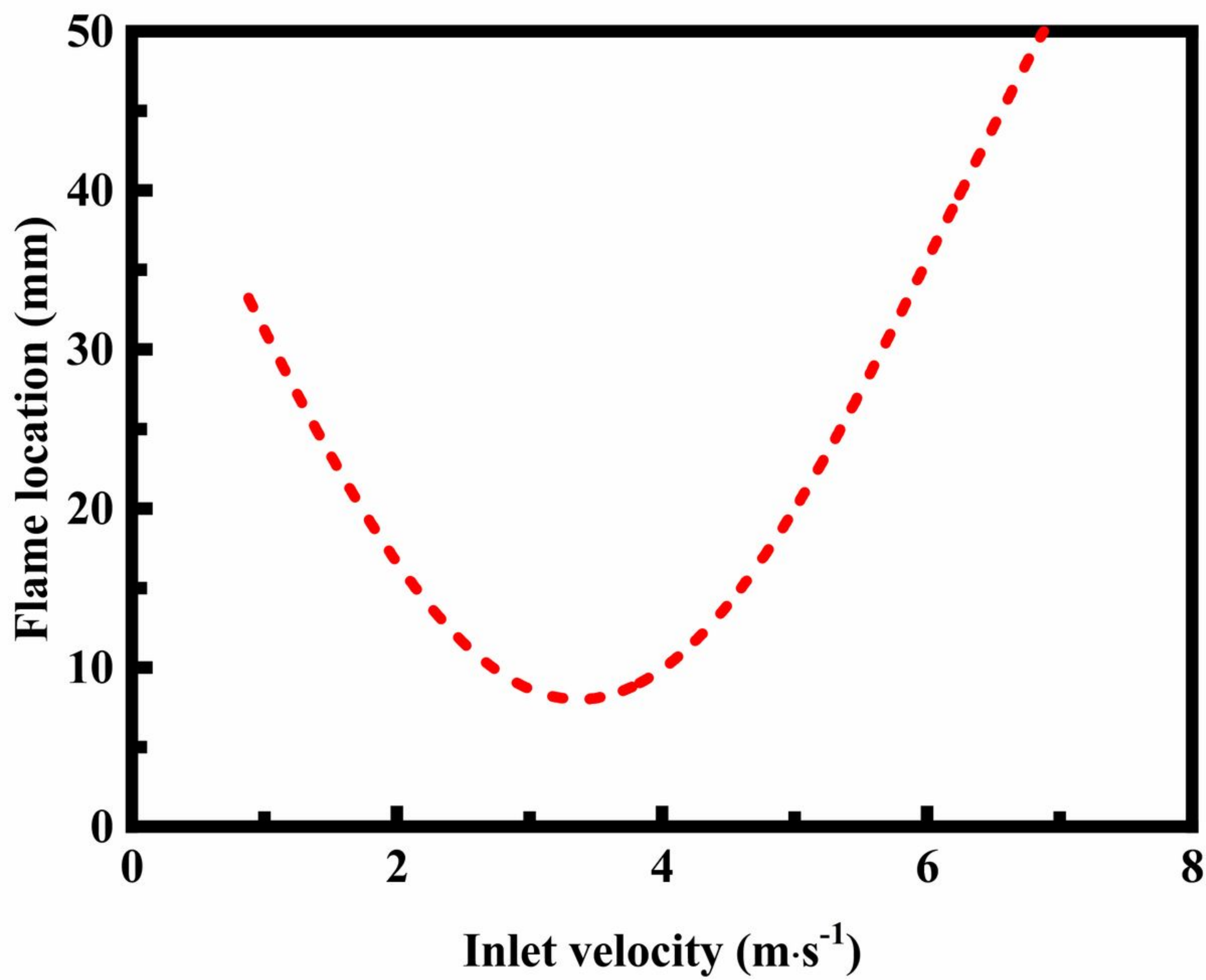

Figure 4

Flame location as a function of inlet velocity. A minimum flame location exists. For fast flows, blowout occurs, whereas for slow flows, extinction occurs due to slow convective heat transfer.

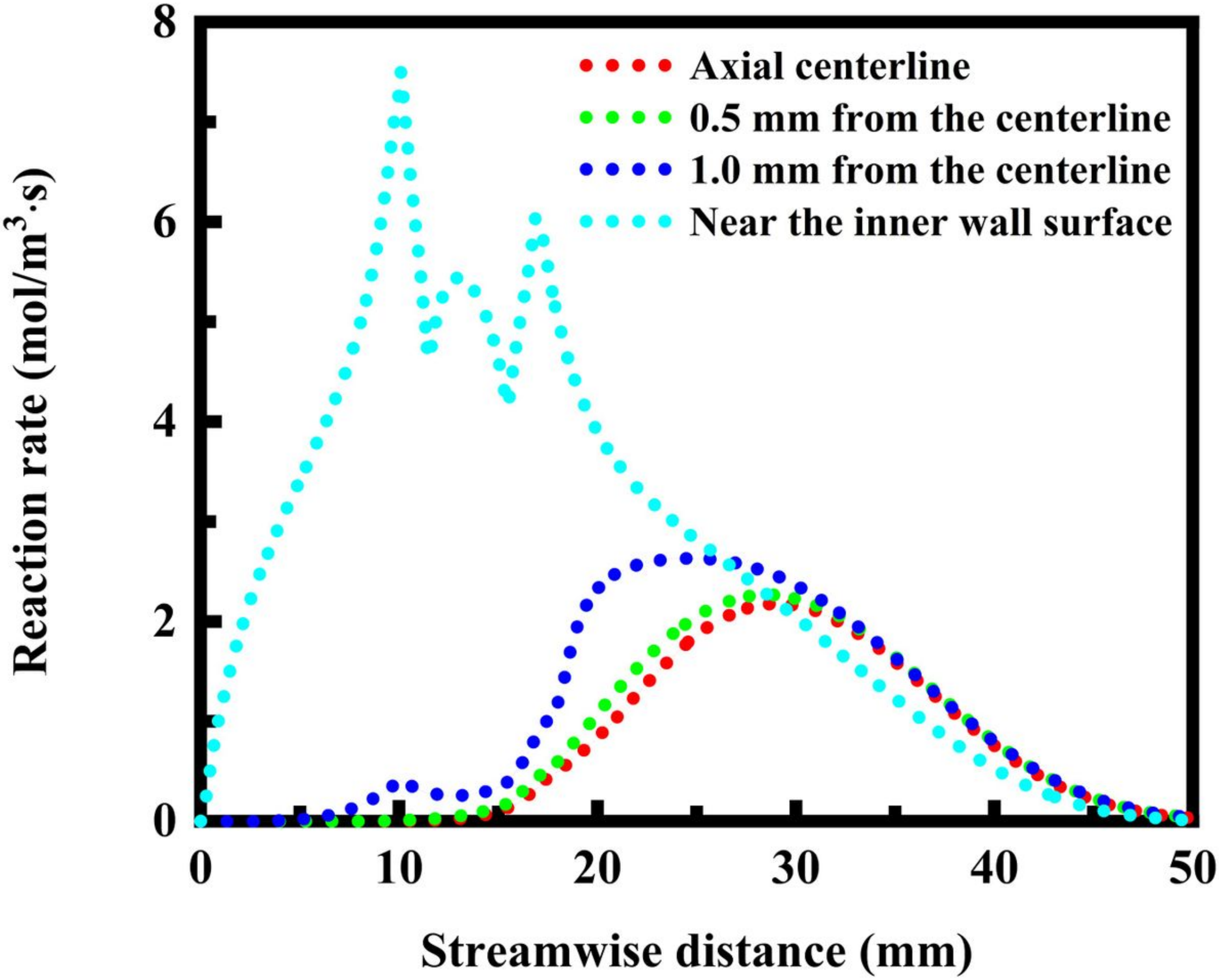

Figure 5

Transverse rate profiles of the combustion reaction at different distances from the axial centerline. The admixture inlet velocity is 0.3 m/s.

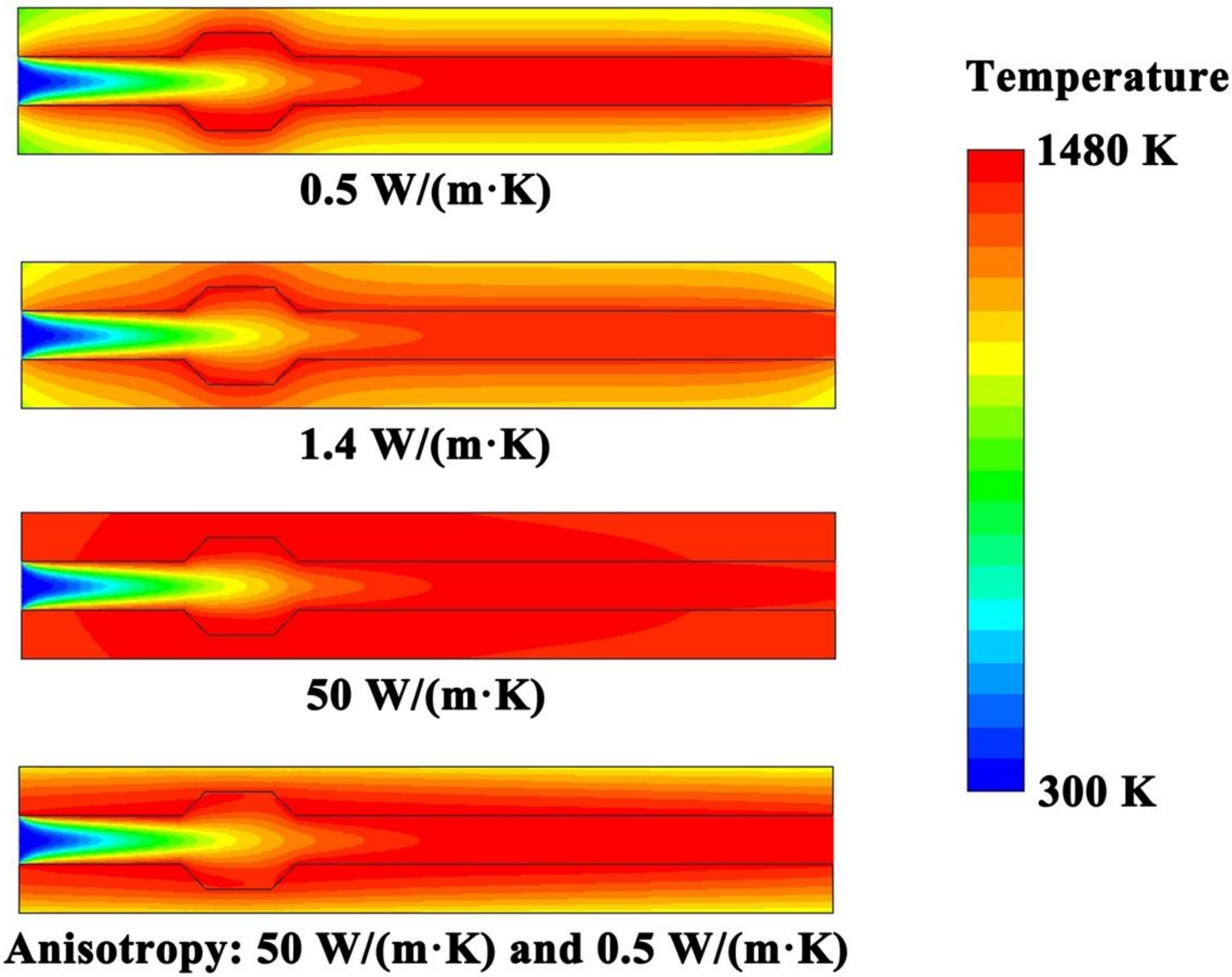

Figure 6

Contour plots of temperature at different thermal conductivities. The thermal conductivity of the anisotropic solid material is 50 W/(m×K) in the longitudinal direction and 0.5 W/(m×K) in the transverse direction.