

# Effect of wall material thermal conductivity on the butane flame stability of microscale gas fired burners

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## Abstract

The effect of wall material thermal conductivity on butane flame stability is investigated for microscale gas fired burners. The present study aims to provide a fundamental understanding of the butane flame stability of microscale gas fired burners at different wall material thermal conductivities. Particular emphasis is placed upon the stability limits over a range of equivalence ratios and the effect of wall material thermal conductivity on the butane flame stability. The results indicate that the wall material thermal conductivity is vital in determining the butane flame stability of the gas fired burners, as the walls are responsible for the majority of the upstream heat transfer as well as the external heat losses. The most effective way of increasing the lean stability limits of the burner is an increase in primary stream inlet temperature. Completing the combustion process near homogeneous stoichiometric conditions, by intensifying the mixing process, may increase nitrogen oxides emissions. To ensure that the combustion process of the furnace is not adversely affected by the presence of the device, the device should not adversely interfere with the flow of products of combustion away from the combustion zone for each burner. Low wall thermal conductivities result in large axial wall-temperature gradients and high maximum temperatures. High wall thermal conductivity leads to uniform temperature profiles without hotspots. Low wall thermal conductivities cause the flame to shift downstream. Increasing wall thermal conductivity has little effect on flame location unless there are significant external heat losses. Typical ceramics allow maximum external heat loss coefficients. 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. The inlet flow velocity plays a competing role in flame stability. There is only a relatively narrow envelope of flow rates within which combustion can be stabilized. The maximum fluid temperature exceeds the adiabatic flame temperature of butane-air mixture computed for room temperature.

**Keywords:** Burners; Combustion; Emissions; Extinction; Flames; Stability

## 1. Introduction

Premixed gas burners used in boilers, heat pumps, hot water heaters and other applications provide a high heat release in a small area while providing low pollutant gas combustion product emissions. Burners which are used in chemical and manufacturing processes often suffer from the problem of matching the heat flux produced by the burner and placed into the space to be heated in the furnace or heat exchanger to the actual load required in order to maximize the amount of heat flux which is being efficiently used, to further maximize the actual rate of production or rate of the process and to reduce problems such as coking, in process heaters for refineries, for example [1, 2]. Such burners, may also occasionally suffer from operational drawbacks, such as instability of the flame relative to the flame holder, which may be evidenced in terms of lift off of the flame from the burner tile, or flame noise and pulsation [3, 4]. In addition, such burners may often produce undesirable levels of emissions, particularly

oxides of nitrogen [5, 6]. Many conventional gas-fired burners use a diffusion flame combustion process in which combustion occurs over a range of equivalence ratios, including high temperature, lean regions where thermal nitrogen oxides form [7, 8]. The term "nitrogen oxides" is intended to refer to any molecular species consisting of nitrogen and oxygen [9, 10], for example, nitric oxide, nitrogen dioxide, nitrous oxide, dinitrogen tetroxide, or combinations thereof. Nitrogen oxides surface as pollutants in a wide variety of contexts. Primarily, nitrogen oxides appear as pollutants in combustion processes. Many approaches have been taken to affect the removal and decomposition of nitrogen oxides from gaseous mixtures containing them [11, 12]. One known method for reducing peak flame temperatures is to use a combustion process which creates a fuel-rich primary combustion region and subsequent air staging with corresponding heat loss, resulting in lowering the overall combustion equivalence ratio to achieve complete combustion [13, 14]. Another known method for reducing peak flame temperatures relates to a combustion process that operates with a fuel-lean primary combustion region and fuel staging in order to raise the equivalence ratio [15, 16]. However, such known methods of staged fuel combustion rely upon a diffusion flame to produce the lean primary stage. External flue gas recirculation can be added to such known methods for further reducing nitrogen oxides.

In the combustion of gaseous fuels, nitrogen oxides are formed primarily through fixation of molecular nitrogen and oxygen in the combustion air [17, 18]. It is known that thermal nitrogen oxides formation depends on the existence of flame regions with relatively high temperatures and excess oxygen [19, 20]. Many conventional combustion methods for reducing nitrogen oxides are based upon avoiding such conditions [21, 22]. It is necessary to consider the prompt nitrogen oxides formation process in order to reach very low nitrogen oxides levels. Reactions between hydrocarbon fragments and molecular nitrogen can lead to the formation of bound nitrogen species, such as hydrogen cyanide, which can subsequently be oxidized to nitrogen monoxide. Such processes become significant relative to the thermal mechanism under moderately fuel-rich conditions at relatively low temperatures [23, 24]. Avoiding such conditions can reduce prompt nitrogen oxides contributions. Additionally, these burners often employ pilot flames for establishing the primary flame region over the burner in a furnace [25, 26]. The pilot, even though small in heat release may contribute to overall burner emissions, particularly of oxides of nitrogen, under ultra-low nitrogen oxides operation. It is of great importance to provide a burner which has greatly reduced emissions, particularly of oxides of nitrogen [27, 28]. It is also of great importance to provide a burner system which is capable of enabling active management and variation of the heat flux in order to allow for the optimization of the heating process and modify the heat flux of the burner to avoid process shutdowns, while maximizing furnace availability [29, 30]. It is very necessary to provide a pilot for a burner, such as may be used in chemical plant process heaters and the like, which provides the establishment of the primary flame region while contributing less to the heat released by the burner and contributing less to the emissions produced by the burner, particularly oxides of nitrogen. It is also very necessary to provide a gaseous fuel burner system which provides a well-organized flame with no significant regions of lean high temperature conditions, which are known to contribute to increased nitrogen oxides emissions.

Combustion processes which burn fossil fuels introduce emissions into the atmosphere which have been linked with harmful effects. Environmental regulations have been enacted to limit the concentrations of these emissions in the exhaust gases from combustion processes [31, 32]. Nitrogen oxides emissions arise from nitrogen present in the combustion air and from fuel-bound nitrogen in hydrocarbons if such fuels are burned [33, 34]. Conversion of fuel-bound nitrogen to nitrogen oxides depends on the amount and reactivity of the nitrogen compounds in the fuel and the amount of oxygen in the combustion zone [35, 36]. Conversion of fuel-bound nitrogen is not present in processes using fuels, for example, natural gas, which contain no fixed nitrogen compounds [37, 38]. Conversion of atmospheric nitrogen present in the combustion air to nitrogen oxides is temperature dependent. In

general, the greater the flame temperature in the combustion zone, the greater the resultant nitrogen oxides content in the emissions. Nitrogen oxides conversion increases drastically at temperatures greater than 1800 K if oxygen is present.

Many industrial processes, such as forging, reheating, and melting of glass or aluminum, are carried out in high temperature, gas-fired furnaces [39, 40]. In such high temperature processes, air used in the combustion process is frequently preheated. Preheating the air reduces the amount of fuel needed, increasing thermal efficiency, but increases the temperature of the flame, which increases nitrogen oxides content [41, 42]. Thus, a higher temperature burner which is capable of reducing nitrogen oxides emissions without sacrificing thermal efficiency is needed [43, 44]. One way of reducing nitrogen oxides content which has been effective in processes using nitrogen bearing fuels is to create a fuel-rich combustion zone followed by a fuel-lean combustion zone [45, 46]. This can be achieved by staging the introduction of air into the combustion chamber. The fuel-rich zone contains less than the theoretical or stoichiometric amount of oxygen. Thus, less oxygen is available to convert the nitrogen-to-nitrogen oxides. Recirculating flue gas into the flame is another technique to limit nitrogen oxides emissions [47, 48]. The recirculated flue gas reduces the oxygen concentration in the reactants and reduces the flame temperature by cooling the combustion products, thereby lowering nitrogen oxides content. Additionally, nitrogen oxides present in the recirculated flue gas can be further destroyed by reburning. The flue gases can also be used for other purposes, such as preheating the combustion air or vaporizing liquid fuels.

Despite previous work, there are a number of unanswered questions regarding flame stability at the microscale. Examples include the role of wall material thermal conductivity in flame stability. The present study is focused primarily upon the effect of wall material thermal conductivity on the butane flame stability of microscale gas fired burners. The two primary mechanisms for quenching in these burners are thermal and radical quenching. Increased heat-transfer coefficients are inherent to microscales, because for a fixed Nusselt number, the heat-transfer coefficient scales with the inverse of the length scale. The high heat-transfer rates increase the heat lost from the reaction, reducing the operating temperatures and causing the combustion to extinguish. At the same time, the increased mass transfer within the system, coupled with the high surface-area-to-volume ratio, causes radical adsorption onto the walls, followed by radical recombination. This dearth of radicals quenches the homogeneous chemistry. Another mechanism for loss of stability is blowout, which occurs when the burner exit velocity exceeds the flame burning velocity. The present study aims to provide a fundamental understanding of the butane flame stability of microscale gas fired burners at different wall material thermal conductivities. Particular emphasis is placed upon the stability limits over a range of equivalence ratios and the effect of wall material thermal conductivity on the butane flame stability.

## 2. Methods

A surface flame holder apparatus is configured to be disposed substantially within the bore of a burner. The flame holder apparatus supports and maintains a flame, resulting from the combustion of a mixture of gaseous fuel and combustion air, on an outer surface of the surface flame holder, the mixture of gaseous fuel and combustion air being established at a location remote from the surface flame holder. The surface flame holder apparatus includes means for establishing a region of recirculation of combustion gases, in the vicinity of the surface flame holder apparatus, for facilitating maintenance of the flame, in the surface of the surface flame holder apparatus. Means are provided for delivering a mixture of gaseous fuel and combustion air to the surface flame holder apparatus.

The pilot flame, which typically, will be kept burning even once the main burner flame is ignited, also resides in the primary flame region. A low-emissions secondary flame region is created by igniting a substantially uniform mixture of fuel, air and flue-gas which is swirling around the primary lean-premixed flame. The fuel-flue-gas mixture is generated by injecting fuel inward in passages which pass

through the burner, thereby entraining flue gases. The surface flame holder apparatus is formed, in part, as a substantially cylindrical flame holder member, having a first diameter, operably configured to receive therethrough the mixture of gaseous fuel and combustion air, for ignition thereof for establishment of the flame on the outer surface thereof. The substantially cylindrical flame holder member may be formed, in one case as a cylindrical metal tube having a plurality of perforations therethrough. In another case, the substantially cylindrical flame holder member may be formed as a cylindrical tube formed from a substantially porous flame-resistant material. The pilot burner apparatus also includes an imperforate disc member, having a second diameter, operably arranged on the substantially cylindrical flame holder member, at a position substantially downstream relative to the substantially cylindrical flame holder member.

In this manner, an extremely uniform and well-organized flame is produced, with no significant regions of lean high temperature conditions. The nitrogen oxides emissions are therefore extremely low. Low flame temperatures, caused by extensive recirculation of flue gas into the flame, are responsible for the overall very low emissions. The means for establishing a region of recirculation of combustion gases comprises preferably an annular disc, having a third diameter, and a central aperture therein, in which the central aperture is associated with the means for delivering the mixture of gaseous fuel and combustion air. The substantially cylindrical flame holder member may be arranged on the annular disc, at a position substantially upstream relative to the substantially cylindrical flame holder, so that the substantially cylindrical flame member is between the imperforate disc and the annular disc, in a sandwiched configuration. Preferably, the third diameter of the annular disc is substantially greater than the second diameter of the substantially cylindrical member, so that gases passing the periphery of the annular disc, will be prompted to move in a toroidal path downstream of the periphery of the annular disc, in turn, prompting the gases to circulate in the vicinity of the outer surface of the substantially cylindrical flame holder member. Preferably, the first diameter of the imperforate disc is less than the third diameter of the annular disc.

The lean mixture entering this recirculation region is ignited by the surface flame and then allows the flame to propagate outward to the main circulation region. A large bluff-body type recirculation region is generated downstream of the pilot-flame-holder assembly. These flow field interactions enable this pilot configuration to stably ignite and maintain extremely lean and flue-gas containing main burner flames. The pilot burner apparatus also may include means for maintaining the imperforate disc, the substantially cylindrical flame holder member and the annular disc in the sandwiched configuration, while substantially precluding the exertion of undesired compressive forces on the substantially cylindrical flame holder apparatus, which may be a plurality of spacer members operably disposed between the annular disc and the imperforate disc for maintaining the annular disc and the imperforate disc at a minimum desired spacing from one another. Preferably, the means for delivering a mixture of gaseous fuel and combustion air to the surface flame holder apparatus further comprises a tubular member, operably connecting the annular disc to a source of mixed gaseous fuel and combustion air. The pilot burner apparatus may also include means for igniting the mixture of gaseous fuel and combustion air delivered to the flame holder apparatus.

The transport and diffusion of the gas flow and fuel are calculated by using such methods as calculus of finite differences, finite element analysis, and finite volume analysis and discretizing the fluid equations. The steady-state continuity, momentum, energy, and species equations in the fluid phase and the steady-state energy equation in the solid phase are discretized using a finite-volume method. The flow is laminar. The aspect ratio of the system is so high that any surface-to-surface radiation is most likely emitted and absorbed at nearly the same axial location. Therefore, radiation is omitted from the simulations performed in this work to focus on the effect of diffusive and convective heat transport on flame stability. The boundary conditions used in this model are given as follows. At the inlet a fixed flat

velocity profile is assumed. For the species and energy equations, the convective portions of the equations are fixed, and the diffusive portions are calculated implicitly. At the interface between the fluid and the solid, no slip and no normal species diffusive flux boundary conditions are applied. The heat flux at this interface is calculated using Fourier's law and continuity in temperature and heat flux is ensured. A symmetry boundary condition is applied at the centerline between the two plates. At the exit, the pressure is specified and the remaining variables are calculated assuming far-field conditions, namely zero diffusive flux of species or energy normal to the exit. In the bulk of the wall the energy equation is solved. The exterior convective heat-transfer coefficient is only used for the calculation of the heat flux of the exterior wall edge boundary condition. This heat-transfer coefficient lumps the details of heat loss from the burner and of the process that utilizes the heat generated by the burner. The left and right wall edges are taken to be insulated.

Since the actual flame is extremely thin, it is necessary to generate a calculation grid smaller than the flame band thickness in order to obtain a precise calculation. When such calculation grids are applied to a combustor, the number of calculation grids becomes enormous and the calculation cost becomes very expensive. By considering the flame surface area per unit volume, it is possible to calculate the flame propagation precisely even when the calculation grid is larger than the flame band thickness. Non-uniform node spacing is employed in this work, with more nodes in the reaction zone. The number of nodes varies depending on dimensions. The fluid viscosity, specific heat, and thermal conductivity are calculated by a mass-fraction-weighted average of species properties. The specific heat is calculated using a piecewise polynomial fit of temperature. The fluid density is calculated using the ideal gas law. The conservation equations are solved implicitly with a steady-state segregated solver using an under-relaxation method. The segregated solver first solves the momentum equation, then the continuity equation, and then updates the pressure and mass flow rate. The conservation equations are then checked for convergence. Convergence is determined from the residuals of the conservation equations as well as the difference between subsequent iterations of the solution. The momentum, species, and energy equations are discretized using a second-order upwind approximation. In order to achieve convergence as well as compute extinction points, natural parameter continuation is implemented. The calculation time of each simulation varies, depending on the difficulty of the problem and the initial guess.

### 3. Results and discussion

The effect of main stream inlet temperature on the stability limits is illustrated in Figure 1 for the opposed reacting jet combustor over a range of equivalence ratios. Fuel lean combustion promises to be an effective means of limiting pollutant formation. Very lean combustion however adversely affects the stability of the combustion process. Thus, initial efforts are directed toward determining the lean stability limits. The primary variables which affect the stability limits of the opposed reacting jet are jet stream equivalence ratio, jet stream flow rate, and main stream inlet temperature. The main stream equivalence ratio at blowout can be reduced by increasing the jet stream equivalence ratio, however the net result is little or no reduction in the equivalence ratio of the recirculation region. Thus, extending the stability limits to lower equivalence ratios through a variation in the jet stream composition does not appear useful to gas turbine applications. Stable operation with both a lean primary and jet stream can be accomplished by increasing the jet exit velocity. An upper limit of 200 meters per second is imposed on the jet velocity in the present investigation due to a desire to avoid compressibility effects encountered at Mach numbers greater than 0.6. Compressibility effects threaten the convergence of the numerical solution and change the nature of the governing equations from elliptic to hyperbolic. In the present investigation, a jet exit velocity of 90 meters per second is selected. This minimized the number of grid points required for the numerical solution while at the same time providing a flame zone large enough to make possible good spatial resolution in the composition and temperature measurements. The most effective way of

increasing the lean stability limits of the opposed reacting jet combustor is found to be an increase in primary stream inlet temperature. For a jet exit velocity of 90 meters per second and a primary stream velocity of 7 meters per second, an inlet temperature of 600 K allows stable operation to be maintained at an overall equivalence ratio as low as 0.38. An increase in jet velocity will of course reduce this stability limit further.

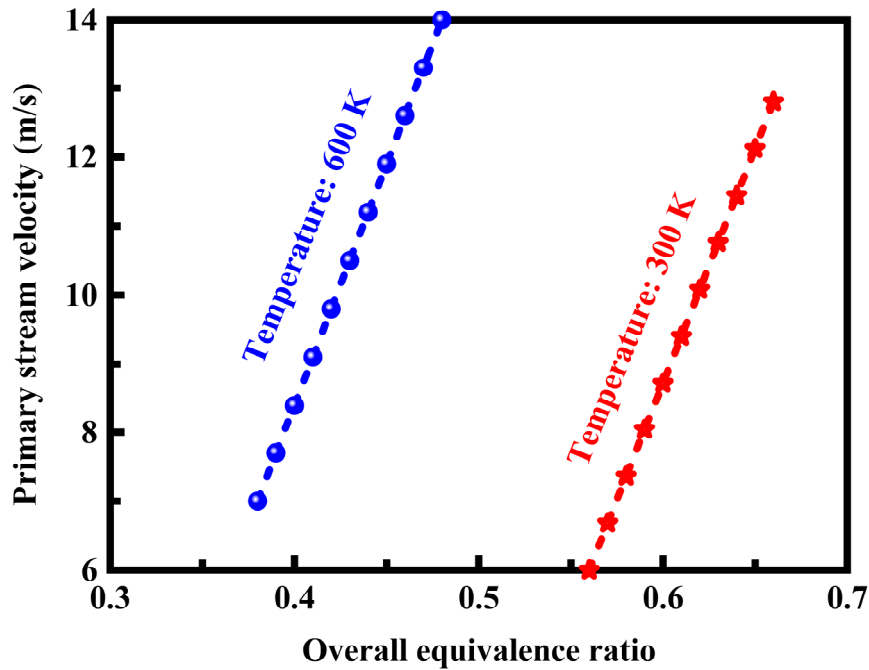


Figure 1. Effect of main stream inlet temperature on the stability limits of the opposed reacting jet combustor over a range of equivalence ratios.

The fluid centerline nitrogen oxides concentration and carbon dioxide mole fraction profiles are presented in Figure 2 along the length of the gas fired burner. The design controls nitrogen oxides emission by reducing the contact time of the hot nitrogen molecules with atmospheric oxygen and conducting the combustion process at a low temperature. Fuel atomization and mixing of the reactants must be improved to complete the combustion rapidly and therefore reduce the residence time to a minimum for the reacting species that produce nitrogen oxides. The reduction of flame temperature is accomplished by radiating heat away from the flame and by diluting the bulk of the reactants with an inert gas. However, use of intense mixing for improved fuel atomization does not result in a low level of nitrogen oxides emissions, but rather results in a high level of nitrogen oxides emissions. Completing the combustion process near homogeneous stoichiometric conditions, by intensifying the mixing process, further increases nitrogen oxides emissions. There are many combustion and burner modification techniques which can reduce the nitrogen oxides emission of gas-fired burners. These techniques include flue gas recirculation [49], staged combustion [50], ultra-high aeration [51], and burner design or redesign [52], as well as flame inserts and secondary air baffling [53, 54], which may be of particular interest. The total system of the burner would have the potential to enjoy numerous benefits in operation such as: a) achievement of higher furnace throughput by modification of flame shape to both optimize the heat flux profile and improve the balance of heat transfer to individual passes; b) detection of coking; c) altering of the heat flux profile to maximize furnace availability and productivity after the onset and buildup of coking and; d) predictive emissions monitoring. The total system of the burner has several advantages: a) much lower emissions; b) practical designs which can meet substantially all potential user requirements; c) the system is retrofittable into many if not most existing furnaces and process heaters; d) no external flue gas recirculation is required; and e) no special treatment of the gaseous fuel is required to obtain optimal furnace performance.

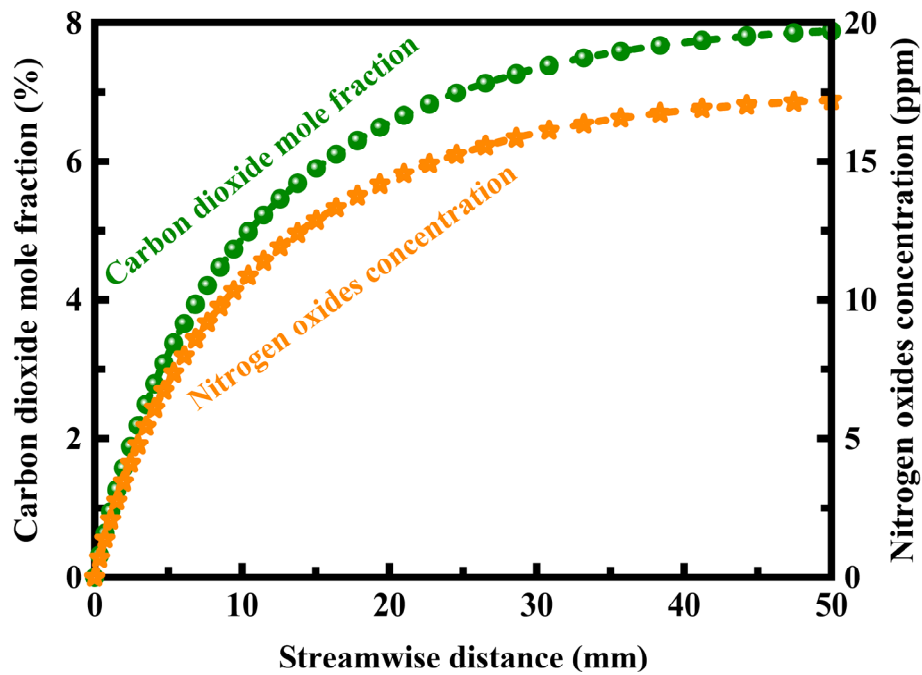


Figure 2. Fluid centerline nitrogen oxides concentration and carbon dioxide mole fraction profiles along the length of the gas fired burner.

The radial nitrogen oxides concentration and carbon dioxide mole fraction profiles are presented in Figure 3 along the height of the gas fired burner. As a result of the combustion process, combustion systems normally generate gaseous combustion products which include oxides of nitrogen which are vented to atmosphere as flue gas. It is desirable to limit these nitrogen oxides emissions since nitrogen oxides are considered a pollutant and combustion systems sold in certain jurisdictions must meet strict nitrogen oxides emission standards. The special device is a piece of material which is sized, configured, and positioned relative to the combustion flame produced by the burner to temper the combustion flame by absorbing thermal energy from the combustion flame. The device is designed to absorb thermal energy from the combustion flame at a rate which limits peak flame temperatures and residence times at these peak flame temperatures to levels which inhibit formation of nitrogen oxides, while allowing substantially complete combustion of fuel supplied to the burner. To ensure that the combustion process of the furnace is not adversely affected by the presence of the device, the device should not adversely interfere with the flow of products of combustion away from the combustion zone for each burner. Further, the device should be relatively easy and inexpensive to manufacture and easy to install, so that the device is practical from a cost-effectiveness viewpoint and so that the device is suitable for retrofitting furnaces having such burners. In addition, preferably, the device is made of a material, such as stainless steel, which is resistant to oxidation at the relatively high combustion flame temperatures, and which radiates thermal energy, which it absorbs from the combustion flame, to its surroundings. Also, if the burner is a two-zone combustion type burner, it is desirable to position and configure the device relative to the combustion flame to aerodynamically smooth at least a portion of the periphery of the combustion flame. This inhibits formation of eddies by near-stoichiometric mixtures of combustion substances at the periphery of the combustion flame which are capable of forming relatively large amounts of nitrogen oxides. Of course, different regions of the combustion flame have different peak flame temperatures and different residence times at these peak flame temperatures depending on their location in the combustion flame. Normally, the temperature of a given region of the combustion flame will vary within a certain temperature range as a function of time during any time period of operation of the burner and will remain at the peak flame temperature within this temperature range for a certain amount of residence time during this time period of operation of the burner. Gaseous fuels are injected along tangential air inlet slits into

the combustion air stream, whereas liquid fuels, such as heating oil, are injected preferably via a central nozzle at the burner head. At the burner outlet, the resulting eddy current bursts open at a change in the cross-section, inducing a backflow zone used for stabilizing the flame while the burner is being operated. In order to prevent interference with the flow field under the conditions of use in gas turbines, even if fuels of different origin and composition are used, and in this way always achieve a safe flame position, downstream from the swirl generator a mixing section may be provided that ensures a better premixing of different types of fuels.

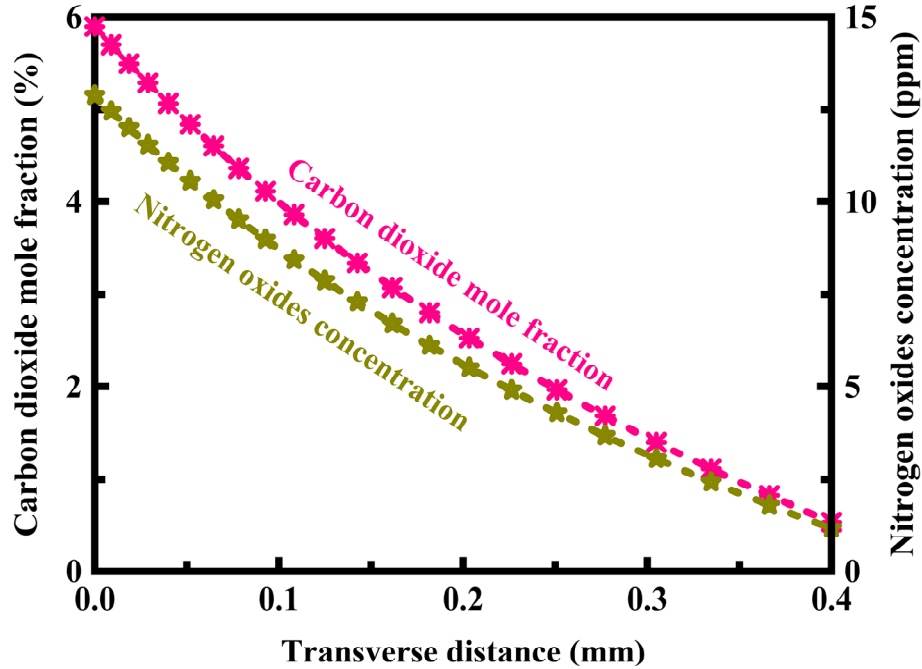


Figure 3. Radial nitrogen oxides concentration and carbon dioxide mole fraction profiles along the height of the gas fired burner.

The effect of wall thermal conductivity on the wall outer edge temperature of the gas fired burner is illustrated in Figure 4 along the length of the burner. The material thermal conductivity affects the temperature profile within the wall and the possibility of hot spots. For low-wall-thermal-conductivity materials, significant axial temperature gradients are observed. Hotspot temperatures in excess of 2000 K can occur, an undesirable situation, as it exceeds the maximum operating temperatures of most materials of construction [55, 56]. Exceedingly high wall temperatures are characteristic of thermally stabilized burners [57, 58]. As the wall thermal conductivity increases, the wall temperature profiles become more uniform and the wall hot spot is eliminated. Despite the apparent advantages of a higher wall thermal conductivity for material stability, most materials that offer high conductance are metals, and therefore would not be inert to radical quenching. A more reasonable solution would be thicker walls of a more inert material that may have a lower thermal conductivity. Low wall thermal conductivities result in large axial wall-temperature gradients and high maximum temperatures. High wall thermal conductivity leads to uniform temperature profiles without hotspots. Flame surface area density is defined as the flame surface per unit volume and serves as a method of modeling the flame propagation based on the fact that the flame progression transports, generates, and diffuses the flame surface area density. The flame propagation is estimated by modeling the flame generation in such a manner that the flame generation resulting from laminar flow is inversely proportional to the chemical reaction characteristic time and proportional to the flame stretch rate. After combustion begins, the combustion first starts as a laminar flame. The growth of the flame is expressed by expressing the generation of the flame surface area density in terms of the growth of the laminar flame. The generation of the flame surface area density is expressed by combining the growth resulting from the mode of combustion, namely the laminar



combustion flame growth. The laminar combustion flame growth is inversely proportional to the chemical reaction characteristic time and a function of the Reynolds number. The laminar combustion flame growth is proportional to both the laminar flame speed and to the ratio of the temperature of a burned portion to the temperature of an unburned portion. The generation of laminar combustion and the resistance imposed on the flame by air can be expressed and the flame propagation can be predicted with good accuracy with respect to combustion modes that are dominated by laminar combustion. It is possible to predict the flame propagation at fields where at the beginning of combustion the turbulence is very weak and laminar combustion dominates due to a very small Reynolds number. Consequently, it is possible to reproduce a situation in which the flame speed increases as the turbulence of the field strengthens and the flame propagation in various fields of weak turbulence can be predicted.

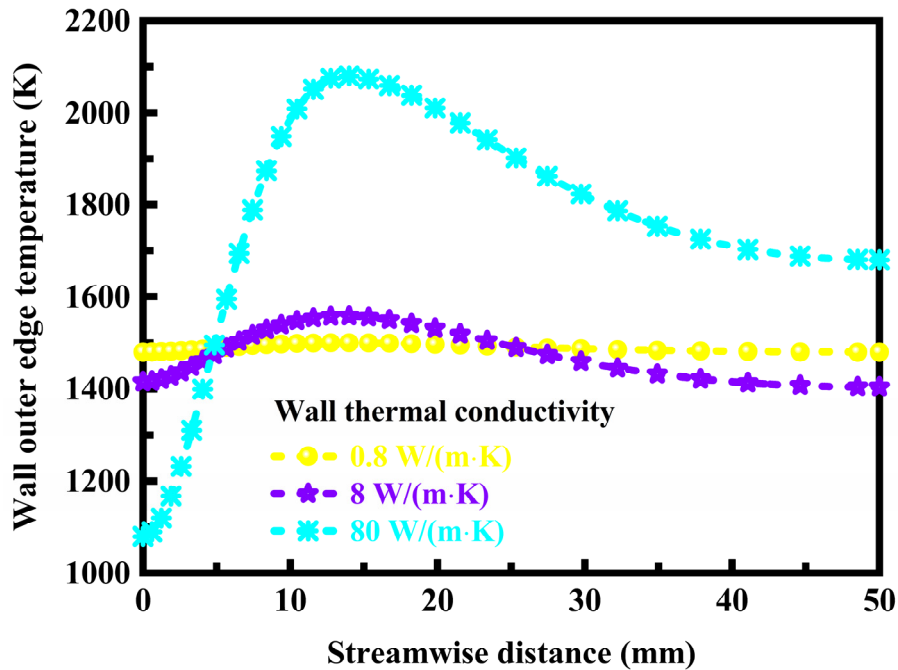


Figure 4. Effect of wall thermal conductivity on the wall outer edge temperature of the gas fired burner along the length of the burner.

The effect of wall thermal conductivity on the flame location of the gas fired burner is illustrated in Figure 5 at different external heat-transfer coefficients. The location of the flame shifts as a function of operating parameters. The flame location as a convenient criterion for the stability or robustness of a burner is defined as the axial position with the highest reaction rate. As the wall thermal conductivity decreases to low values, the flame location shifts downstream for all external heat-transfer coefficients. For high wall thermal conductivity and low external-heat-loss coefficients, increasing wall thermal conductivity to high values has a minor effect on the flame location. On the other hand, for high external-heat-loss coefficients in systems, increasing wall thermal conductivity shifts the reaction downstream. This nonlinear behavior is caused by the interaction between two competing modes of heat transfer, namely upstream heat transfer through the walls to preheat the feed, and transverse heat transfer resulting in heat loss to the surroundings. The former is critical for ignition and flame stabilization in microchannels, as it allows preheating of the feed without the need for an external preheater. If the upstream heat transfer is insufficient to increase the fluid temperature to the ignition temperature, a flame is not stabilized within the burner. Since the conductivity of the walls is orders of magnitude higher than that of the fluid, heat conduction through the walls is the primary mechanism of upstream heat transfer. When this upstream heat transfer is limited by low wall thermal conductivity, it takes a greater distance to achieve the preheating, resulting in the reaction zone shifting downstream. This makes the flame less stable. For a given wall thermal conductivity, increasing the external heat loss coefficient shifts the

reaction zone downstream as more of the heat generated is lost to the surroundings. Low wall thermal conductivities cause the flame to shift downstream. Increasing wall thermal conductivity has little effect on flame location unless there are significant external heat losses. The wall thermal conductivity alone does not determine the relative upstream heat transfer in the system. The wall thickness and the gap distance also play an important role. As the gap distance increases, the time scales for heat transfer from the reaction zone to the walls and from the hot walls to the inlet reactants increases because of the increased length scale. As a result of the latter, the flame location occurs further downstream and more conductive materials are needed for stable operation. As a result of the former, the system is more robust to exterior heat losses. In particular, for highly conductive materials and large external heat-transfer coefficients, the flame location does not shift downstream with increasing wall thermal conductivity. Consequently, the larger gap makes the burner very robust with respect to heat losses.

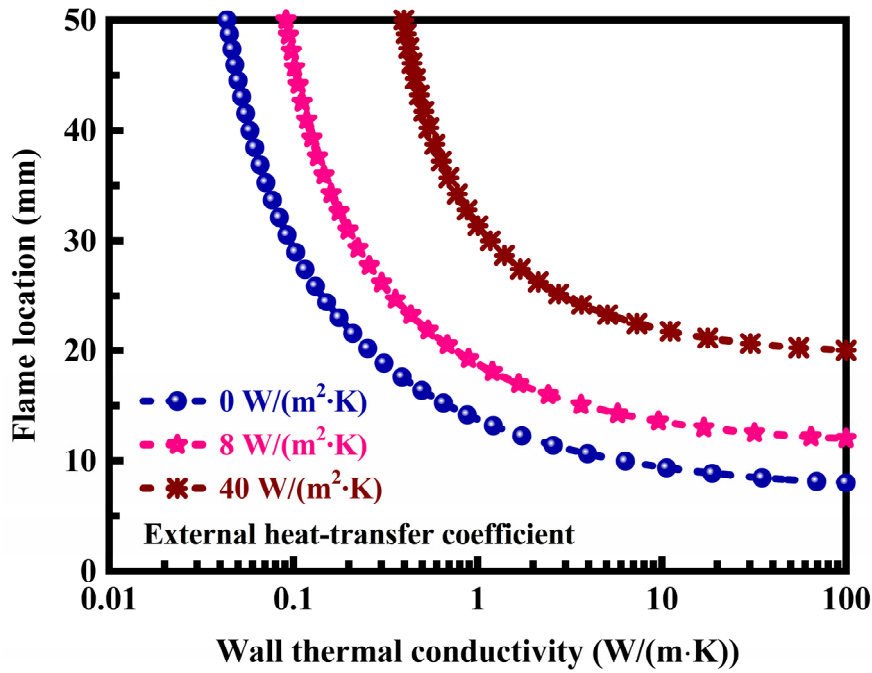


Figure 5. Effect of wall thermal conductivity on the flame location of the gas fired burner at different external heat-transfer coefficients.

The effect of wall thermal conductivity on the critical external heat loss coefficient of the gas fired burner is illustrated in Figure 6 for the butane fuel. 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. The conductivity of several materials is also indicated by arrows. There exists a critical wall thermal conductivity for butane-air mixtures below which combustion cannot be self-sustained, even with insulating walls. 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 alumina and silica. The behavior observed 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. Typical ceramics allow maximum external heat loss coefficients. 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. Flames are quenched in these small dimensions because of two primary mechanisms, namely thermal and radical quenching. Thermal quenching occurs when sufficient heat is removed through the walls, that combustion cannot be self-sustained. Radical quenching occurs via adsorption of radicals on the system walls and subsequent recombination, which results in

lack of homogeneous chemistry. The small scales of these systems make them significantly more prone to both quenching mechanisms because of the high surface area to volume ratios, namely enhanced heat transfer from the flame to the walls and increased radical mass transfer. In addition to flame quenching, blowout can occur when the burner exit velocity exceeds the flame burning velocity. In this mechanism, the reaction shifts downstream until it exits the burner. While flame propagation at the microscale is feasible, the interplay of kinetics and transport in flame stability and combustion characteristics of these systems is poorly understood. The inability of conducting spatially resolved measurements, inherent to the microscale, underscores the need for detailed mathematical modeling.

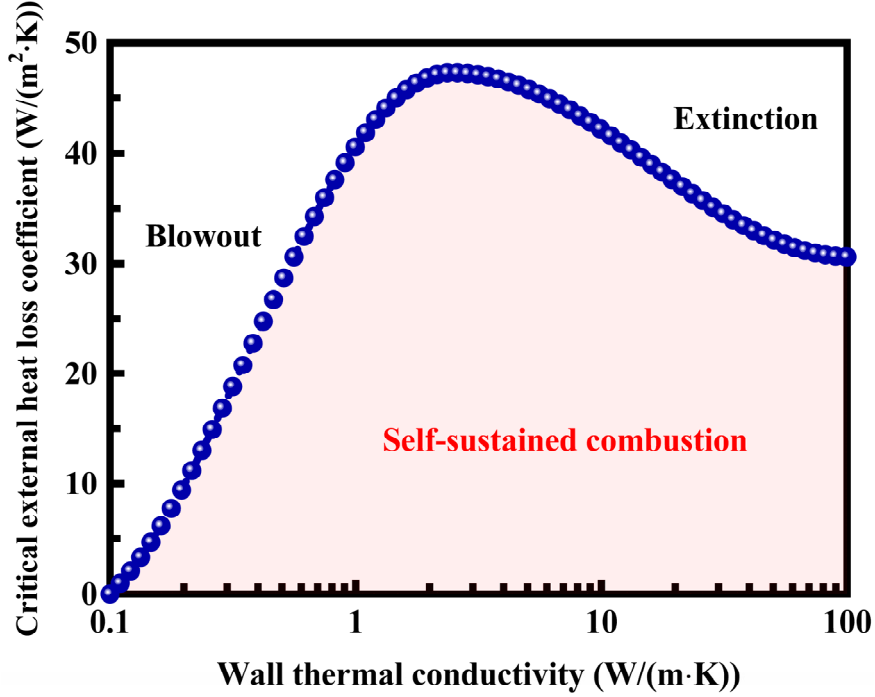


Figure 6. Effect of wall thermal conductivity on the critical external heat loss coefficient of the gas fired burner for the butane fuel.

The effect of wall thermal conductivity on the critical flow velocity of the gas fired burner is illustrated in Figure 7 at a fixed external heat loss coefficient. The upper curve represents the high-velocity limit, resulting in blowout due to decreased convective timescales. The lower curve represents the low-velocity limit, resulting in flame stability loss due to reduced heat generation. Between these curves stabilized combustion is allowed, whereas outside the envelope, self-sustained combustion is impossible. Smaller wall thermal conductivities allow stabilized combustion for lower flow rates. Lower flow rates require less upstream heating and more insulation against exterior heat losses. At the other extreme, higher wall thermal conductivities result in maximum allowable flow rates, but the increased heat losses prohibit low flow rates. This relationship is important when designing devices. When a low-power device is desired, more insulating materials should be preferred. On the other hand, when a high-power device is desired, more conductive materials should be chosen. The present study focuses upon thermal stability. However, other material properties, such as allowable operating temperatures [59, 60], radical sticking [61, 62], and mechanical strength [63, 64], along with the burner efficiency should be considered when choosing a material for construction and designing burner dimensions [65, 66]. The inlet flow velocity plays a competing role in flame stability. Low flow velocities result in reduced power generation. On the other hand, high flow velocities decrease the convective timescale below that of the upstream heat transfer through the walls. As a result, there is only a relatively narrow envelope of flow rates within which combustion can be stabilized. When a low-power device is being designed, more insulating materials should be favored to minimize external heat losses. Conversely, a high-power device would favor more conductive materials.

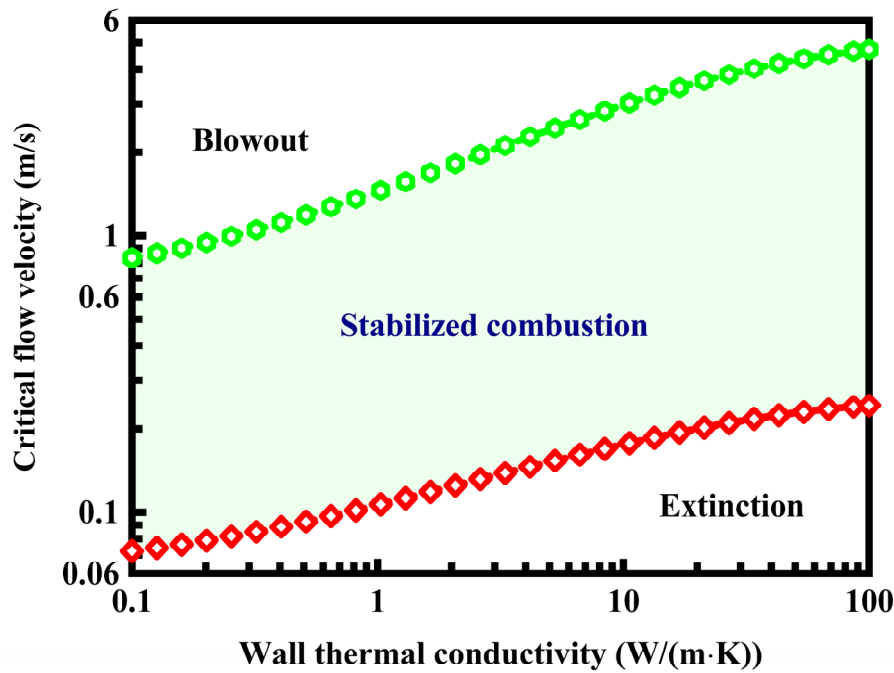


Figure 7. Effect of wall thermal conductivity on the critical flow velocity of the gas fired burner at a fixed external heat loss coefficient.

The fluid centerline temperature profiles are presented in Figure 8 along the length of the burner with preheating, combustion, and post-combustion or cooling regions. For most cases studied, burners exhibit similar combustion characteristics that are summarized here. There are three regions in these burners, namely preheating, combustion, and post-combustion or cooling regions. The width of these regions changes as a function of operating conditions, and their distinction is not always as sharp. In the preheating region, the wall temperature is significantly higher than the fluid temperature, so energy transfers from the wall to the fluid. The wall thermal conductivity is significantly larger than that of the fluid mixture, so most of the upstream conductive heat flux occurs within the walls of the reactor. This energy is brought upstream from the post-combustion region where walls are considerably hot. Since the mixture warms up from the wall towards the centerline, ignition occurs near the wall and the flame stabilizes at the centerline. This ignition mode is different from the case where outside preheating is used to ignite the mixture. In the latter case, ignition occurs at the centerline. Once the fluid reaches the ignition temperature, there is an inflection point in the temperature profile. The mixture combusts rapidly, releasing heat, which causes a sharp rise in the fluid temperature in the combustion region. The combustion zone is relatively narrow, a characteristic of highly activated reactions. Even at these relatively small scales, the transverse heat transfer within the fluid is much slower than the rate of heat release so that the fluid centerline temperature in this zone approaches approximately the adiabatic flame temperature. Combustion at the lower adiabatic flame temperature produces a correspondingly lesser amount of nitrogen oxides production. In the post-combustion region, after the reactants are consumed, the reaction stops, the fluid cools down to the wall temperature, and the walls are cooled by exterior heat losses. There are no significant axial or transverse gradients within this zone. In non-adiabatic cases, both the fluid and the wall would eventually reach room temperature in sufficiently long burners. In some cases, the maximum fluid temperature exceeds the adiabatic flame temperature of butane-air mixture computed for room temperature. Traditional continuous stirred tank reactor or plug flow reactor analysis suggests that this is impossible to achieve with one-step chemistry. However, in this distributed model, the wall acts as a conduit for heat transfer from the hot exiting products to the cold entering reactants. This link results in a heat recycle within the system, which increases the temperatures near the inlet and allows a maximum temperature that is greater than the adiabatic flame temperature. Because of the

overall energy conservation, the exiting fluid temperature is in these cases lower than the adiabatic flame temperature.

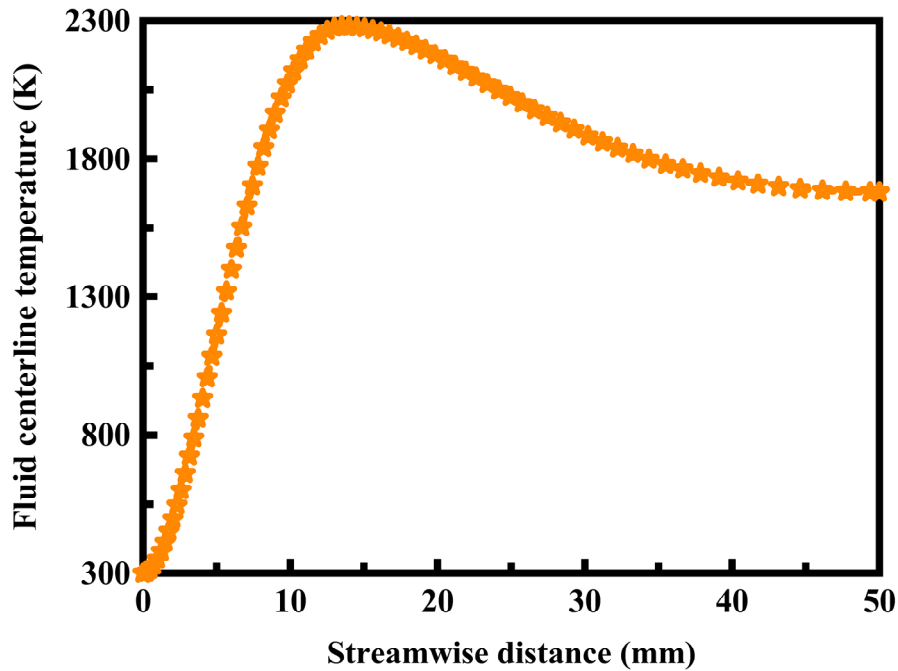


Figure 8. Fluid centerline temperature profiles along the length of the burner with preheating, combustion, and post-combustion or cooling regions.

#### 4. Conclusions

The effect of wall material thermal conductivity on butane flame stability is investigated for microscale gas fired burners in terms of wall outer edge temperature, flame location, critical external heat loss coefficient, and critical flow velocity. The present study aims to provide a fundamental understanding of the butane flame stability of microscale gas fired burners at different wall material thermal conductivities. Particular emphasis is placed upon the stability limits over a range of equivalence ratios and the effect of wall material thermal conductivity on the butane flame stability. The major conclusions are summarized as follows:

- The most effective way of increasing the lean stability limits of the burner is an increase in primary stream inlet temperature.
- Completing the combustion process near homogeneous stoichiometric conditions, by intensifying the mixing process, may increase nitrogen oxides emissions.
- To ensure that the combustion process of the furnace is not adversely affected by the presence of the device, the device should not adversely interfere with the flow of products of combustion away from the combustion zone for each burner.
- Low wall thermal conductivities result in large axial wall-temperature gradients and high maximum temperatures. High wall thermal conductivity leads to uniform temperature profiles without hotspots.
- Low wall thermal conductivities cause the flame to shift downstream. Increasing wall thermal conductivity has little effect on flame location unless there are significant external heat losses.
- Typical ceramics allow maximum external heat loss coefficients. 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.
- The inlet flow velocity plays a competing role in flame stability. There is only a relatively narrow envelope of flow rates within which combustion can be stabilized.
- The maximum fluid temperature exceeds the adiabatic flame temperature of butane-air mixture

computed for room temperature.

## References

- [1] B.H. Chao. Instability of burner-stabilized flames with volumetric heat loss. *Combustion and Flame*, Volume 126, Issues 1-2, 2001, Pages 1476-1488.
- [2] S. Kumar, P.J. Paul, and H.S. Mukunda. Studies on a new high-intensity low-emission burner. *Proceedings of the Combustion Institute*, Volume 29, Issue 1, 2002, Pages 1131-1137.
- [3] I. Cerri, G. Saracco, and V. Specchia. Methane combustion over low-emission catalytic foam burners. *Catalysis Today*, Volume 60, Issues 1-2, 2000, Pages 21-32.
- [4] Y. Ogawa, N. Saito, and C. Liao. Burner diameter and flammability limit measured by tubular flame burner. *Symposium (International) on Combustion*, Volume 27, Issue 2, 1998, Pages 3221-3227.
- [5] V. Knop, A. Nicolle, and O. Colin. Modelling and speciation of nitrogen oxides in engines. *Proceedings of the Combustion Institute*, Volume 34, Issue 1, 2013, Pages 667-675.
- [6] G.-U. Baek, H.K. Nguyen, S.H. Yoon, J.H. Moon, S.H. Jo, S.J. Park, J.Y. Kim, S.J. Kim, S.J. Yoon, H.W. Ra, S.M. Yoon, J.G. Lee, K.-B. Lee, and T.-Y. Mun. Simultaneous reduction of nitrogen oxides and sulfur dioxide in circulating fluidized bed combustor during oxy-coal combustion. *Journal of Cleaner Production*, Volume 370, 2022, Article Number: 133484.
- [7] F. Pecquery, V. Moureau, G. Lartigue, L. Vervisch, and A. Roux. Modelling nitrogen oxide emissions in turbulent flames with air dilution: Application to LES of a non-premixed jet-flame. *Combustion and Flame*, Volume 161, Issue 2, 2014, Pages 496-509.
- [8] F. Normann, K. Andersson, B. Leckner, and F. Johnsson. Emission control of nitrogen oxides in the oxy-fuel process. *Progress in Energy and Combustion Science*, Volume 35, Issue 5, 2009, Pages 385-397.
- [9] H. Tsukahara, T. Ishida, and M. Mayumi. Gas-phase oxidation of nitric oxide: Chemical kinetics and rate constant. *Nitric Oxide*, Volume 3, Issue 3, 1999, Pages 191-198.
- [10] P. Glarborg, A.D. Jensen, and J.E. Johnsson. Fuel nitrogen conversion in solid fuel fired systems. *Progress in Energy and Combustion Science*, Volume 29, Issue 2, 2003, Pages 89-113.
- [11] D. Laraqui, O. Allgaier, C. Schönnenbeck, G. Leyssens, J.-F. Brilhac, R. Lomba, C. Dumand, and O. Guézet. Experimental study of a confined premixed metal combustor: Metal flame stabilization dynamics and nitrogen oxides production. *Proceedings of the Combustion Institute*, Volume 37, Issue 3, 2019, Pages 3175-3184.
- [12] A. Cuoci, A. Frassoldati, T. Faravelli, and E. Ranzi. Formation of soot and nitrogen oxides in unsteady counterflow diffusion flames. *Combustion and Flame*, Volume 156, Issue 10, 2009, Pages 2010-2022.
- [13] M.D. Sirignano, V. Nair, B. Emerson, J. Seitzman, and T.C. Lieuwen. Nitrogen oxide emissions from rich premixed reacting jets in a vitiated crossflow. *Proceedings of the Combustion Institute*, Volume 37, Issue 4, 2019, Pages 5393-5400.
- [14] S.C. Hill and L.D. Smoot. Modeling of nitrogen oxides formation and destruction in combustion systems. *Progress in Energy and Combustion Science*, Volume 26, Issues 4-6, 2000, Pages 417-458.
- [15] C.T. Bowman. Control of combustion-generated nitrogen oxide emissions: Technology driven by regulation. *Symposium (International) on Combustion*, Volume 24, Issue 1, 1992, Pages 859-878.
- [16] J.C. Hewson and F.A. Williams. Rate-ratio asymptotic analysis of methane-air diffusion-flame structure for predicting production of oxides of nitrogen. *Combustion and Flame*, Volume 117, Issue 3, 1999, Pages 441-476.
- [17] L.-E. Mand and B. Leckner. The role of fuel volatiles for the emission of nitrogen oxides from fluidized bed boilers-A comparison between designs. *Symposium (International) on Combustion*,

Volume 23, Issue 1, 1991, Pages 927-933.

- [18] J.M. Card, R. Rydén, and F.A. Williams. Influences of flame-vortex interactions on formation of oxides of nitrogen in curved methane-air diffusion flamelets. *Combustion and Flame*, Volume 105, Issue 3, 1996, Pages 373-380.
- [19] P. Schmittl, B. Günther, B. Lenze, W. Leuckel, and H. Bockhorn. Turbulent swirling flames: Experimental investigation of the flow field and formation of nitrogen oxide. *Proceedings of the Combustion Institute*, Volume 28, Issue 1, 2000, Pages 303-309.
- [20] S. Goel, A. Sarofim, P. Kilpinen, and M. Hupa. Emissions of nitrogen oxides from circulating fluidized-bed combustors: Modeling results using detailed chemistry. *Symposium (International) on Combustion*, Volume 26, Issue 2, 1996, Pages 3317-3324.
- [21] S.-H. Kim, M. Kim, Y. Yoon, and I.-S. Jeung. The effect of flame radiation on the scaling of nitrogen oxide emissions in turbulent hydrogen non-premixed flames. *Proceedings of the Combustion Institute*, Volume 29, Issue 2, 2002, Pages 1951-1956.
- [22] S.-H. Kim, Y. Yoon, and I.-S. Jeung. Nitrogen oxides emissions in turbulent hydrogen jet non-premixed flames: Effects of coaxial air and flame radiation. *Proceedings of the Combustion Institute*, Volume 28, Issue 1, 2000, Pages 463-471.
- [23] D. Phong-Anant, L.J. Wibberley, and T.F. Wall. Nitrogen oxide formation from Australian coals. *Combustion and Flame*, Volume 62, Issue 1, 1985, Pages 21-30.
- [24] P. Glarborg, J.A. Miller, and R.J. Kee. Kinetic modeling and sensitivity analysis of nitrogen oxide formation in well-stirred reactors. *Combustion and Flame*, Volume 65, Issue 2, 1986, Pages 177-202.
- [25] W.R. Boyette, A.M. Bennett, E. Cenker, T.F. Guiberti, and W.L. Roberts. Effects of pressure on soot production in piloted turbulent non-premixed jet flames. *Combustion and Flame*, Volume 227, 2021, Pages 271-282.
- [26] J. Kim, A. Satija, R.P. Lucht, and J.P. Gore. Effects of turbulent flow regime on perforated plate stabilized piloted lean premixed flames. *Combustion and Flame*, Volume 211, 2020, Pages 158-172.
- [27] J.O.L. Wendt and J.M. Ekmann. Effect of fuel sulfur species on nitrogen oxide emissions from premixed flames. *Combustion and Flame*, Volume 25, 1975, Pages 355-360.
- [28] R.C. Flagan, S. Galant, and J.P. Appleton. Rate constrained partial equilibrium models for the formation of nitric oxide from organic fuel nitrogen. *Combustion and Flame*, Volume 22, Issue 3, 1974, Pages 299-311.
- [29] T.L. Rashwan, J.L. Torero, and J.I. Gerhard. Heat losses in a smouldering system: The key role of non-uniform air flux. *Combustion and Flame*, Volume 227, 2021, Pages 309-321.
- [30] V.A. Alekseev and A.A. Konnov. Data consistency of the burning velocity measurements using the heat flux method: Hydrogen flames. *Combustion and Flame*, Volume 194, 2018, Pages 28-36.
- [31] G.N. Richter, H.C. Wiese, and B.H. Sage. Oxides of nitrogen in combustion. Premixed flame. *Combustion and Flame*, Volume 6, 1962, Pages 1-8.
- [32] S. Singh, W. Grosshandler, P.C. Malte, and R.W. Crain. Oxides of nitrogen formed in high-intensity methanol combustion. *Symposium (International) on Combustion*, Volume 17, Issue 1, 1979, Pages 689-699.
- [33] R.F. Sawyer and I. Glassman. Gas-phase reactions of hydrazine with nitrogen dioxide, nitric oxide, and oxygen. *Symposium (International) on Combustion*, Volume 11, Issue 1, 1967, Pages 861-869.
- [34] J.D. Allen. Probe sampling of oxides of nitrogen from flames. *Combustion and Flame*, Volume 24, 1975, Pages 133-136.
- [35] R.C. Seagrave, H.H. Reamer, and B.H. Sage. Oxides of nitrogen in combustion: Oscillatory combustion at elevated pressure. *Combustion and Flame*, Volume 9, Issue 1, 1965, Pages 7-18.
- [36] R.F. Sawyer and I. Glassman. The reactions of hydrogen with nitrogen dioxide, oxygen, and mixtures of oxygen and nitric oxide. *Symposium (International) on Combustion*, Volume 12, Issue 1, 1969,



Pages 469-479.

- [37] F. Kaufman and J. Kelso. Reactions of atomic oxygen and atomic nitrogen with oxides of nitrogen. *Symposium (International) on Combustion*, Volume 7, Issue 1, 1958, Pages 53-56.
- [38] C.P. Fenimore. Formation of nitric oxide from fuel nitrogen in ethylene flames. *Combustion and Flame*, Volume 19, Issue 2, 1972, Pages 289-296.
- [39] M. Landfahner, C. Schluckner, H. Gerhardt, T. Zmek, J. Klarner, and C. Hochenauer. Numerical model incorporating different oxidizer in a reheating furnace fired with natural gas. *Fuel*, Volume 268, 2020, Article Number: 117185.
- [40] K. Qiu and A.C.S. Hayden. Direct thermal to electrical energy conversion using very low bandgap TPV cells in a gas-fired furnace system. *Energy Conversion and Management*, Volume 79, 2014, Pages 54-58.
- [41] P.C. Malte and D.T. Pratt. Measurement of atomic oxygen and nitrogen oxides in jet-stirred combustion. *Symposium (International) on Combustion*, Volume 15, Issue 1, 1975, Pages 1061-1070.
- [42] C.P. Fenimore. Effects of diluents and mixing on nitric oxide from fuel-nitrogen species in diffusion flames. *Symposium (International) on Combustion*, Volume 16, Issue 1, 1977, Pages 1065-1071.
- [43] S.D. Jaeger and A.V. Tiggelen. Comparative study of flame propagation in compounds containing nitrogen oxides. *Combustion and Flame*, Volume 3, 1959, Pages 187-200.
- [44] L. Phillips and R. Shaw. Reactions of methyl and methoxyl radicals with nitrogen dioxide and nitric oxide. *Symposium (International) on Combustion*, Volume 10, Issue 1, 1965, Pages 453-461.
- [45] R.C. Seagrave, H.H. Reamer, and B.H. Sage. Oxides of nitrogen in combustion: Some microscopic measurements. *Combustion and Flame*, Volume 8, Issue 1, 1964, Pages 11-19.
- [46] H.K. Newhall. Kinetics of engine-generated nitrogen oxides and carbon monoxide. *Symposium (International) on Combustion*, Volume 12, Issue 1, 1969, Pages 603-613.
- [47] R.W. Schefer and R.F. Sawyer. Lean premixed recirculating flow combustion for control of oxides of nitrogen. *Symposium (International) on Combustion*, Volume 16, Issue 1, 1977, Pages 119-134.
- [48] M. Abián, Á. Millera, R. Bilbao, and M.U. Alzueta. An experimental and modeling study of the influence of flue gases recirculated on ethylene conversion. *Combustion and Flame*, Volume 161, Issue 9, 2014, Pages 2288-2296.
- [49] M. Abdelaal, M. El-Riedy, A.M. El-Nahas, and F.R. El-Wahsh. Characteristics and flame appearance of oxy-fuel combustion using flue gas recirculation. *Fuel*, Volume 297, 2021, Article Number: 120775.
- [50] F. Okasha. Staged combustion of rice straw in a fluidized bed. *Experimental Thermal and Fluid Science*, Volume 32, Issue 1, 2007, Pages 52-59.
- [51] A.H. Lefebvre. Pollution control in continuous combustion engines. *Symposium (International) on Combustion*, Volume 15, Issue 1, 1975, Pages 1169-1180.
- [52] R. Ciardiello, R.S. Pathania, I.E. Helou, and E. Mastorakos. Lean blow-off investigation in a linear multi-burner combustor operated in premixed and non-premixed modes. *Applications in Energy and Combustion Science*, Volume 9, 2022, Article Number: 100041.
- [53] R.M. Kumar, S. Adhikari, B. Emerson, C.A. Fugger, and T. Lieuwen. Blowoff of bluff body flames: Transient dynamics and three dimensional effects. *Combustion and Flame*, Volume 244, 2022, Article Number: 112245.
- [54] R.W. Bryers. Fireside slagging, fouling, and high-temperature corrosion of heat-transfer surface due to impurities in steam-raising fuels. *Progress in Energy and Combustion Science*, Volume 22, Issue 1, 1996, Pages 29-120.
- [55] V. Mislavskii, N. Pestovskii, S. Tskhai, B. Kichatov, V. Gubernov, V. Bykov, and U. Maas. Diffusive-thermal pulsations of burner stabilized methane-air flames. *Combustion and Flame*, Volume 234, 2021, Article Number: 111638.



- [56] S. Nechipurenko, T. Miroshnichenko, N. Pestovskii, S. Tskhai, B. Kichatov, V. Gubernov, V. Bykov, and U. Maas. Experimental observation of diffusive-thermal oscillations of burner stabilized methane-air flames. *Combustion and Flame*, Volume 213, 2020, Pages 202-210.
- [57] A. Moroshkina, V. Mislavskii, B. Kichatov, V. Gubernov, V. Bykov, and U. Maas. Burner stabilized flames: Towards reliable experiments and modelling of transient combustion. *Fuel*, Volume 332, Part 2, 2023, Article Number: 125754.
- [58] I. Yakovlev, A. Maznoy, and S. Zambalov. Pore-scale study of complex flame stabilization phenomena in thin-layered radial porous burner. *Combustion and Flame*, Volume 231, 2021, Article Number: 111468.
- [59] S. Ishizuka. Flame propagation along a vortex axis. *Progress in Energy and Combustion Science*, Volume 28, Issue 6, 2002, Pages 477-542.
- [60] A. Umemura and K. Tomita. Rapid flame propagation in a vortex tube in perspective of vortex breakdown phenomena. *Combustion and Flame*, Volume 125, Issues 1-2, 2001, Pages 820-838.
- [61] Y.S. Ko and S.H. Chung. Propagation of unsteady tribrachial flames in laminar non-premixed jets. *Combustion and Flame*, Volume 118, Issues 1-2, 1999, Pages 151-163.
- [62] A. Gorczakowski, A. Zawadzki, J. Jarosinski, and B. Veyssiere. Combustion mechanism of flame propagation and extinction in a rotating cylindrical vessel. *Combustion and Flame*, Volume 120, Issue 3, 2000, Pages 359-371.
- [63] M. Fairweather, G.K. Hargrave, S.S. Ibrahim, and D.G. Walker. Studies of premixed flame propagation in explosion tubes. *Combustion and Flame*, Volume 116, Issue 4, 1999, Pages 504-518.
- [64] H.A. Dwyer and T. Hasegawa. Some flows associated with premixed laminar flame propagation in a rotating tube flow. *Proceedings of the Combustion Institute*, Volume 29, Issue 2, 2002, Pages 1471-1477.
- [65] V.S. Santoro, A. Liñán, and A. Gomez. Propagation of edge flames in counterflow mixing layers: Experiments and theory. *Proceedings of the Combustion Institute*, Volume 28, Issue 2, 2000, Pages 2039-2046.
- [66] T. Hasegawa and K. Nishikado. Effect of density ratio on flame propagation along a vortex tube. *Symposium (International) on Combustion*, Volume 26, Issue 1, 1996, Pages 291-297.