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Accuracies of laminar counterflow flame experiments

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ABSTRACT

Counterflow configurations are useful for investigating the structures of premixed, non-premixed, and partially premixed flames. Ignition and extinction conditions also are readily measured in this configuration. There is a wide range of different possible designs of apparatus to be used in such measurements. The choices vary from opposing nozzle flows without any flow-smoothing screens to opposing flows through porous plates. It is desirable to select designs that correspond best to the conditions treated in available codes for calculating reacting flows because this facilitates comparisons of experimental and computational results. The most convenient codes to use are for steady laminar flows with one-dimensional scalar fields, and they often impose rotational plug-flow conditions at the boundaries. Accuracies of axisymmetric counterflow flame measurements in experiments intended to conform to these conditions are estimated here for designs of large aspect ratios with straight-duct feed streams that have multiple-screen flow-smoothing exits. Causes of departures from assumptions underlying computational programs are addressed by methods that involve theoretical analysis, experimental measurement, and axisymmetric computation. It is concluded that experimental results would not be expected to differ from predictions made with plug-flow boundary conditions by more than five percent for properly designed counterflow experiments of this straight-duct, multiple-screen type.

1. Introduction

While there are many reasons for performing combustion experiments, ranging from searching for previously unknown phenomena to improving design, performance, and safety of combustion devices, a prevalent growing motivation is to improve knowledge of underlying transport and chemical-kinetic rate processes, increasing accuracies with which associated parameters are known. Steady counterflows and their variants, such as stagnation flow normal to an inert, impermeable, flat plate or normal to the surface of a solid or liquid-pool fuel, are increasingly becoming the configuration of choice in this quest for greater accuracy. Initial careful work [1,2] – viewed by many as somewhat of a curiosity – for example, a novel way to blow a hole in the center of a flame – the developing realization of the many advantages of the counterflow configuration underlies its emergence.

One advantage is that counterflows enable steady combustion processes to be established away from complicating influences of walls; there is no need to address stabilization-region effects of rim-stabilized or rod-stabilized flames. Another is the inherent stability of the counterflow. The streamline stretching in this configuration helps to dampen disturbances and to prevent some types of combustion instabilities from occurring. It is well suited for experiments at normal atmospheric pressure but also can be adapted for measurements at elevated pressures [3–18], approaching conditions of greater interest in many propulsion and power-production applications. Although planar, two-dimensional counterflow combustors can be (and have been [19,20]) constructed and studied, for most purposes it is simpler and more convenient to select an axisymmetric flow, which makes it unnecessary to consider end effects and which generally exhibits enhanced disturbance-damping abilities.

Use of counterflow combustion experiments to test underlying predictions of these chemically reacting flows requires the availability of numerical methods for solving the sets of partial differential equations that describe the flow. While finite-difference computations can be made for steady, axisymmetric flow [21–27] they become expensive, time-consuming, and often tricky to implement, although important conclusions have recently been drawn from such studies [25–27]. The primary results are the computational demonstrations that, under suitable experimental conditions, with properly chosen boundary conditions one-dimensional codes can be employed with reasonable accuracy [25–27] there being well-defined error metrics on exit-diameter effects [27]. If the problem can be reduced to one of solving only

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ordinary differential equations, then the computations become much simpler, and, moreover, in principle they can be performed with greater accuracy. A number of computer codes of this type are now available for solving counterflow combustion problems, such as Chemkin [28], OpenSMOKE [29], Cosilab [30], FlameMaster [31], Cantera [32], and LOGEsoft [33] (formerly DARS [34]). This strongly motivates designing counterflow experiments that obey the conditions required for accurate descriptions in terms of ordinary differential equations. The present discussion addresses the accuracy with which this objective can be obtained.

2. Limitations on the selection of the type of experiment

The first requirement for meeting the preceding objective is to achieve steady, laminar flow. In general, if the Reynolds number is too high, the flow becomes turbulent. For counterflows, the Reynolds number *Re* may be defined as a representative velocity U of the gas in the approach flow times a characteristic dimension L of the apparatus, divided by a representative kinematic viscosity ν of the gas. In a Tsuji burner[1] [36,37] U would be the air flow velocity in the wind tunnel and L the diameter of the porous tube through which the fuel emerges, but in current counterflows U would be an average of the gas exit velocities from the two opposed tubes or ducts, and L the separation distance between the two duct exits. If the duct diameters were smaller than about half the separation distance, then it would be better to use the exit-duct diameter in *Re*.

The critical value of $Re = UL/\nu$ above which the counterflow begins to become turbulent actually is not very well established, but because of the stabilizing influences of the configuration it is certainly well above the well-known value of about 2000 for fully developed pipe flow. Corrections for effects of the Reynolds number in laminar flow tend to be of the order of $1/\sqrt{Re}$, and these corrections then can be as small as one percent without there being a tendency for the counterflow to become turbulent. In fact, when there is interest in studying turbulent counterflow combustion experimentally, it is necessary to resort to turbulence-producing grids or perforated plates [38,39], and it is difficult to achieve high-intensity turbulence when that is desired [39].

The axes of the exit ducts in laminar counterflow combustion experiments are placed vertically because if they were not then buoyancy would introduce asymmetry. Unless the temperature of the gas leaving the upper duct is superadiabatic (a condition almost always too hot to achieve), the gas flow between the upper exit and the flame is buoyantly unstable. While a considerable amount of information is available on critical conditions for stability in primarily stagnant layers [40], despite extensive more recent work, such as that which is newly reviewed [41,42], the perturbative influences of the counterflow on the onset of this instability have not been addressed and deserve future study. The stabilizing stretching of the counterflow tends to delay the instability, but stable laminar flow is unattainable in these counterflow experiments at sufficiently high pressures. The relevant stability parameter is the Grashof number, which here is of the order of gL^3/ν^2, where g denotes the acceleration of gravity. This parameter, which varies strongly with the length L and the pressure p (being proportional to p^2L^3) is of the order of 1000 in room-temperature air at normal atmospheric pressure if L is 10^{-2} m, which exceeds the critical value for stability [40]. Although the thickness of the layer of adverse density gradient is less than the duct-exit separation distance, it cannot be made appreciably less than 10^{-3} m, whence p as high as 10 atm places most experiments beyond the stability limit. By decreasing dimensions, employing a design with a nozzle diameter of 6.5×10^{-3} m, useful data have recently be obtained up to 25 atm [17], roughly consistent with the limiting pressure varying as $L^{3/2}$.

In spite of the fact that detailed theoretical analyses of this Grashof-number instability are unavailable (so that this limiting type of $L^{3/2}$ scaling may be inaccurate), the existence of this effect is well documented in recent experimental work [13–16] and likely affected earlier high-pressure NO measurements [7,8], at relatively high Reynolds numbers and relatively low strain rates, where excessively high NO concentrations were recorded on the air side, the upper, unstable side (especially noticeable in the highest-pressure profile [7], well beyond any reasonable NO production region, probably a result of fine-scale upward convective mixing). In a sense, it is fortunate that Earth's gravity level is low enough to allow stable counterflow laminar combustion experiments to be performed routinely at normal atmospheric pressures. Stable experiments at high pressures would require reduced-gravity platforms, such as the Lunar surface, although replacement of nitrogen by helium can improve the stability at high pressures by increasing ν [12,15,17].

An additional buoyancy-related complication arises if the exit velocities are too low. The flame then has been observed to bulge upward in the center because of buoyancy (although bulging tendencies in the opposite direction have been observed in some small-scale contoured-nozzle designs). In view of the acceleration of gravity at the Earth's surface, for a duct separation distance on the order of 10^{-2} m, exit velocities greater than 0.3 m/s are needed for the imposed acceleration in the counterflow to be comparable with that of buoyancy (an effective Froude number $U^2/(gL)$ greater than unity). The upward bulging becomes pronounced for screened ducts at exit velocities below this, although it can be reduced by increasing the duct diameters. The curvature associated with the bulge is inconsistent with a one-dimensional calculation; however, the formulation may still apply approximately along the centerline. It is straightforward to include the axial buoyancy term in the ordinary differential equations, and when this is done, for most purposes its influence is found to be negligible; it merely modifies the vertical pressure distribution and the flame location. If, however, L is increased much beyond twice the exit diameter, then buoyant instabilities tend to develop that destroy the one-dimensionality associated with expansion about the centerline. Further discussion of the effect may be found in recent references [12,17], couched in terms of a Richardson number, which is essentially the reciprocal of this Froude number.

Given these buoyancy limitation on exit velocities, counterflow combustion experiments performed on the surface of the Earth are necessarily experiments at high *Re*. It is impractical to reduce L much below 10^{-2} m, and with U no less than 0.3 m/s, it would be necessary for ν to exceed 3×10^{-3} m^2/s to have $Re < 1$. This would necessitate producing pressures below 0.03 atm, which would be both difficult and rather uninteresting for most combustion purposes. Low-*Re* conditions could be achieved at normal atmospheric pressure in space experiments, a fact which motivates the performance of such experiments for the purpose of circumventing the buoyancy limitation, but unfortunately no such experiments yet exist. Current experiments not strongly affected by buoyancy typically correspond to *Re* between 300 and 3000. In the present situation, then, there is motivation for detailed theoretical consideration of laminar, high-*Re* limits. Many such investigations have been completed.

It is worth emphasizing that, in numerical computations, there is no particular significance to the fact that in the experiment *Re* will be large. The entire flow field is calculated, with boundary conditions applied at the exits of the ducts. Numerical difficulties concerning spatial resolution could occur if *Re* were extremely large,

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[1] Fuel is injected through the porous walls of a tube whose axis is perpendicular to a uniform air flow in a wind tunnel. This configuration was addressed in the earliest computational work [35].