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Updated jet flame radiation modeling with buoyancy corrections

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ABSTRACT

Radiative heat fluxes from small to medium-scale hydrogen jet flames (<10 m) compare favorably to theoretical predictions provided the product species thermal emittance and optical flame thickness are corrected for. However, recent heat flux measurements from two large-scale horizontally orientated hydrogen flames (17.4 and 45.9 m respectively) revealed that current methods underpredicted the flame radiant fraction by 40% or more. Newly developed weighted source flame radiation models have demonstrated substantial improvement in the heat flux predictions, particularly in the near-field, and allow for a sensible way to correct potential ground surface reflective irradiance. These updated methods are still constrained by the fact that the flame is assumed to have a linear trajectory despite buoyancy effects that can result in significant flame deformation. The current paper discusses a method to predict flame centerline trajectories via a one-dimensional flame integral model, which enables optimized placement of source emitters for weighted multi-source heat flux prediction methods. Flame shape prediction from choked releases was evaluated against flame envelope imaging and found to depend heavily on the notional nozzle model formulation used to compute the density weighted effective nozzle diameter. Nonetheless, substantial improvement in the prediction of downstream radiative heat flux values occurred when emitter placement was corrected by the flame integral model, regardless of the notional nozzle model formulation used.

Introduction

A primary hazard associated with the unintended release and subsequent ignition of hydrogen from storage, transport, and delivery applications is radiant heat flux exposures and elevated temperatures from hydrogen jet flames that can result in potentially lethal burns and severe respiratory damage [1]. Detailed flame simulations have provided useful information about the interplay between flow dynamics and combustion chemistry [2,3], but are prohibitive for practical safety applications due to the significant computational resources required. Reduced order models developed from empirical observation are often used instead to determine hazard boundaries [4–12]. These models require relevant release conditions (e.g., nozzle diameter/shape, mass flow rate, gas type) to estimate flammable envelopes and the amount of flame energy converted into escaping radiant

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energy, defined here as the radiant fraction, χ. Schefer et al. [13] reported that as with hydrocarbon flames, hydrogen jet flame radiant fractions, defined as the radiative energy escaping relative to chemical energy released, exhibit a logarithmic dependence on flame residence time, t_f. However, the absence of CO_2 or soot in the product stream results in lower overall radiant fractions [14]. Based on these observations, Molina et al. [15] developed a unified expression that treated the flame as a blackbody emitter with the radiant fraction expressed a function of flame residence time, adiabatic flame temperature ($T_{ad,H_2} = 2390$ K), and Plank's mean absorption coefficient for the product species ($a_{f,H_2O} = 0.23\ m^{-1}$).

$$\chi = 0.08916 \cdot \log_{10}\left(t_f a_f T_{ad}^4\right) - 1.2172 \quad (1)$$

Note that t_f is in milliseconds. A gap remains between computationally expensive simulations and low-fidelity empirical models that have limited applicability in realistic scenarios. To bridge this gap, Air Products and Chemicals Inc. commissioned radiative heat flux measurements from two large-scale hydrogen flames, and worked with Sandia National Laboratories' Hydrogen Safety, Codes and Standards research group to analyze results and develop improved modeling approaches. Radiant heat flux predictions derived from conventional single point source models [6,11] under-predicted measured values by 40% or more, particularly in the near-field. For most locations, the difference was accounted for if multi-source models were used and reflective surface addition from steel and concrete below the release path was included [16]. The exception was from a radiometer placed directly downstream of the expected flame length, which recorded radiative heat fluxes far below the model predictions. It was noted that curved centerline flame trajectories due to buoyancy effects were not captured and may have increased optical path lengths between the flame and radiometer. The present paper discusses the development of a one-dimensional flame integral model to predict flame centerline trajectories, which can then be used to optimize the source emitter placement. Model entrainment coefficients were calibrated from detailed flame velocity and scalar data and model performance was evaluated against large-scale horizontally propagating hydrogen jet flame images.

Large-scale flame experiments

Two large-scale hydrogen jet fire experiments were conducted at the GL Noble Denton Spadeadam Test Site in North Cumbria, UK. Compressed hydrogen gas was released from a nominal 60 barg stagnation pressure through a horizontally orientated 1 m long stretch of pipe with respective internal diameters of 20.9 and 52.5 mm, and located 3.25 m above the ground. Boundary and ambient condition details for each test are summarized in Table 1 while images of the release setup and delivery system schematic are given in Fig. 1. Since the storage and delivery lines had previously been used for similar tests of natural gas flames, 3 consecutive hydrogen purges were performed prior to the experiments to remove any residual natural gas from the system. A 25 m by 15 m concrete pad below the release path was used to prevent surface dirt entrainment into the flame. To protect against spallation, the pad was further covered with steel sheeting.

Mass flow rates were calculated from upstream temperature measurements and the pressure drop across an orifice plate in accordance with ISO 5167 parts 1 and 2 [17]. Orifice pressure drop and static temperature were respectively measured by a Druck STX 2100 differential pressure transducer (0–2.0 bar range, 0.2% full-scale accuracy) and type 'T' thermocouples with outputs linearized by a Pretop 5331B temperature transmitter (±100 °C, 0.05% full-scale accuracy). Static pressure and temperature were measured at 3 locations in the release pipe via Druck PTX-1400 pressure transducers (0–100 barg range, 0.15% full-scale accuracy) and the same thermocouple systems used for upstream mass flow rate measurements. Incident thermal radiation was measured by a wide-angle Medtherm radiometer (150° field of view, 0.3–11.5 μm transmission, 1.0 s response time, ±5% full-scale accuracy) that was mounted on a tripod and orientated towards the projected flame center. Radiometer measurements were recorded over a 5 s averaging window. Radiometer positions and the predicted flame center for both flames are given in Table 2, while a schematic in Fig. 1 illustrates the relative placement.

Flame envelopes were recorded by 2 standard definition cameras positioned perpendicular to the cross-stream field of view. Visible flame lengths were established by averaging maximum visible extents from each cross stream video image, with standard deviations reported in Table 2. Wind speed/direction, ambient temperature, and relative humidity were measured at a weather tower located ~111 m upstream from the release point. Ambient pressure was reported from a nearby weather station located at Carlisle, Cumbria, UK. The flames were oriented 67° relative to true north. Further details about test setup and operating procedures can be found in Ekoto et al. [16] — note that in Ref. [16] the flame length for the larger release was reported at 48.5 m, which corresponded to the maximum observed flame length rather than the average value of 45.9 m as reported here.

Weighted multi source flame radiation model

Observer heat flux, q, is proportional to the portion of flame surface radiant energy emitted to the observer defined here as the view factor, VF, the total radiative power, S_{rad}, normalized

Table 1 – Boundary and ambient conditions for each large-scale jet flame. Note that wind directions are where the wind is coming from relative to true north while the release direction is the direction of the release path.

Flame	d_j[mm]	$\dot{m}$ [kg/s]	p_0 [barg]	T_0 [K]	RH [%]	T_{amb} [K]	p_{amb} [bar]	u_{wind} [m/s]	φ_{wind} [°]	L_{vis} [m] (rms)
1	20.9	1.0	59.8	308.7	94.3	280	1.022	2.84	68.5	17.4 (1.1)
2	52.5	7.4	62.1	287.8	94.5	280	1.011	0.83	34.0	45.9 (2.5)

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