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Planar momentum-dominated regime of small-scale hydrogen leakage

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ABSTRACT

The geometry of the source of hydrogen leakage is essential in forming hydrogen flow and distribution in air. For example, if the geometry of the source is circular, the behavior of leakage flow becomes axisymmetric and a radial jet is constructed. On the other hand, if the geometry of the source is planar, the behavior of hydrogen leakage becomes planar and a planar jet is constructed. Throughout this article, the problem of momentum-dominated regime of a planar slow-leak hydrogen–air jet resulting from a hydrogen leakage from a planar source is considered. We derive a set of analytical expressions for selected physical turbulent properties. Several quantities of interest are obtained, including the cross-stream velocity, the Reynolds stresses, the velocity-concentration correlation, the dominant turbulent kinetic energy production term, the turbulent eddy viscosity, the turbulent eddy diffusivity, and the turbulent Schmidt number. Moreover, the normalized jet-feed material density and the normalized momentum flux density are correlated.

1. Introduction

The energy content and density of fuels from fossil sources is usually high which motivate their use in many of our daily life applications. However, because of their hazardous consequences to the environment, the search for cleaner sources of energy is an urgent need. So far no alternative clean energy could satisfy our needs, reached to a conclusion. On the other hand, none of the newly introduced energy sources have comparable energy content and density as that of the fossil fuel sources. For example, hydrogen looks appealing as a fuel source because of its lightweight and its high energy content. However, at standard conditions, hydrogen occupies a larger volume that greatly lowers its energy density. In order to increase the energy density of hydrogen, therefore, it is important to store hydrogen in a liquid or compressed form. Unfortunately, hydrogen storage is considerably difficult than that for other fuel gases, which have been, to a large extent, very much comprehended with current technologies. That is, the molecules of hydrogen gas are smaller than all other gases, and it can diffuse through many materials considered airtight or impermeable to other gases. This property makes hydrogen more difficult to contain than other gases. Hydrogen leaks are dangerous in that they pose a risk of fire where they mix with air. That is hydrogen is flammable and explosive over a very wide range of concentrations in air (4–75%) and (15–59%), respectively, at standard atmospheric temperature. Moreover, hydrogen has a lower ignition energy, which is

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about an order of magnitude lower than that for methane and propane and is therefore more easily ignitable. Even an invisible spark or static electricity discharge may have enough energy to cause ignition. Therefore, it is important for hydrogen facilities to be tight proof of hydrogen leakage. The strong possibility of hydrogen leakage can happen mainly for the following reasons. Firstly, long-term exposure of containment materials to hydrogen causes a phenomenon known as hydrogen embrittlement, which may result in cracking and hydrogen leakage. Secondly, the expected extensive usage of hydrogen in various industrial applications increases the risk of its accidental release in hydrogen infrastructure such as storage, bulk transportation and distribution, production and utilization.

Hydrogen leakage may be divided into two classes, the first is a rapid-leak causing combustion, while the other is an unignited slow-leak. However, hydrogen is ignited in air by some source of ignition such as static electricity (autoignition) or any external source. The classic turbulent jet flame models can be used to model the first class of hydrogen leakage (cf. [1,2]). This work is focused on the second class of unignited slow-leaks. In Refs. [3–5], El-Amin and coauthors have introduced boundary layer theory approach to model the concentration layer adjacent to a ceiling wall at the impinging and far regions in both planar and axisymmetric cases for small-scale hydrogen leakage. While in Refs. [6–8], the authors studied the turbulent hydrogen–air jet/plume resulted from hydrogen leakage in open air. SnchezSanz et al. [9] considered a laminar hydrogen jet. Houf and Schefer [10] presented analytical and experimental investigations of small-scale unintended releases of hydrogen. Also, in Ref. [11] they introduced mathematical and physical analyses with numerical investigation of a buoyant jet resulting from hydrogen leakage in air from a horizontal round source. Furthermore, El-Amin et al. [12] derived analytical expressions for plume centerline variables such as radius, velocity, and density deficit, in terms of a single universal function, called plume function. On the other hand, other researchers such as Matssura and coauthors [13–16], and Kikukawa [17] performed CFD simulations of the hydrogen leakage in the air.

Jet is produced when the fluid exits a nozzle with initial momentum and represents an example of free shear flows. In general case of the jet, the initial volume flux is assumed to be zero; however, in the real cases, the jet has a finite source size and initial volume flux. In the pure jet non-buoyant jet the initial momentum flux as a high velocity injection causes the turbulent mixing. In a pure plume the buoyancy flux causes a local acceleration that lead to turbulent mixing. In the general case of a buoyant jet forced plume a combination of initial momentum flux and buoyancy flux is responsible for turbulent mixing (see for example Refs. [18,19]).

Hydrogen distribution measurements in a small-scale leak with neglecting the buoyancy effects are described by Schefer et al. [25]. In their study, they reported that Froude number in the momentum-dominated regime was ($Fr = 268$). The Reynolds number was sufficient for fully developed turbulent flow and buoyancy-generated momentum is negligible. The results showed that hydrogen jets behave similar to jets of helium and conventional hydrocarbon fuels such as methane and propane in the momentum-dominated regime. Moreover, the hydrogen mass fraction centerline decay rate shows z^{-1} dependence, where z is the axial distance from the jet exit. On the other hand, Agrawal and Prasad [20] have derived similarity solutions for several quantities of interest such as Reynolds stress, eddy diffusivities of momentum, etc., for axisymmetric and planar turbulent jets, plumes, and wakes.

Hydrogen leakage may occur from loose fittings, o-ring seals, pinholes, or vents on hydrogen-containing vehicles, buildings, storage facilities, or other hydrogen-based systems. When the geometry of the source of the hydrogen leak is circular, such as a pinhole or an o-ring, the behavior of leakage flow becomes axisymmetric and a radial jet is constructed. In contrast, when the geometry of the source of the hydrogen leak is planar, such as a crack, the behavior of hydrogen leakage becomes planar and a planar jet is constructed. In the previous article of this series, we studied the axisymmetric case [6] of the momentum-dominated regime of a buoyant jet resulting from hydrogen leakage in air, while the current article considers the planar case. Empirical expressions, such as the streamwise and the centerline velocities, and the concentration at any downstream location are used to derive similarity solutions.

2. Governing equations

The streamwise velocity and concentration at any downstream location for a self-similar planner jet, can be approximated by a Gaussian distribution [20–22],

$$U(x,z) = U_{cl}(z)\exp(-\eta^2) \tag{1}$$

$$C(x,z) = C_{cl}(z)\exp(-\lambda^2\eta^2) \tag{2}$$

where $\eta = x/b(z)$ and $b(z) = c_m(z - z_0)$. is the virtual origin, which is the distance above/below the orifice where the flow appears to originate. The measured spread rate c_m varies in the range 0.1–0.13 [25]. The centerline velocity U_{cl} and the centerline concentration C_{cl} varies with $z^{-1/2}$, while the jet width b increases linearly with z [20]. The spread rate for the concentration c_c appears in the formula $\lambda = c_m/c_c$. It is well known that if $c_c \neq c_m$, it means that the velocity and concentration spread have different rates.

The continuity, momentum, and concentration equations in Cartesian coordinates (Fig. 1) for the momentum-dominated regime of a vertical buoyant hydrogen free jet may be written as,

$$\frac{\partial V}{\partial x} + \frac{\partial U}{\partial z} = 0 \tag{3}$$

$$V\frac{\partial U}{\partial x} + U\frac{\partial U}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - \frac{\partial\left(\overline{u^2}\right)}{\partial x} - \frac{\partial(\overline{uv})}{\partial z} \tag{4}$$

$$V\frac{\partial V}{\partial x} + U\frac{\partial V}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - \frac{\partial(\overline{uv})}{\partial x} - \frac{\partial\left(\overline{v^2}\right)}{\partial z} \tag{5}$$

$$V\frac{\partial C}{\partial x} + U\frac{\partial C}{\partial z} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}\right) - \frac{\partial(\overline{vc})}{\partial x} - \frac{\partial(\overline{uc})}{\partial z} \tag{6}$$