5.4 THE STRUCTURE OF HORIZONTAL HYDROGEN-STEAM DIFFUSION FLAMES

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Abstract

This paper summarizes a systematic study on the stability, peak temperature and flame length of various horizontal hydrogen-steam diffusion flames in air. Results from this study are discussed in terms of their impact on hydrogen management in a nuclear containment building after a nuclear reactor accident. They show that, for a certain range of emerging hydrogen-steam compositions, a stable diffusion flame can anchor itself at the break in the primary heat transport system. The length of this flame can be up to 100 times the break diameter. This implies that creation of a stable diffusion flame at the break is a possible outcome of the deliberate ignition mitigation scheme. The high temperature and heat flux from a diffusion flame can threaten nearby equipment. However, due to the presence of steam and turbulent mixing with surrounding air, the peak temperatures of these diffusion flames are much lower than the adiabatic constant pressure combustion temperature of a stoichiometric hydrogen-air mixture. These results suggest that the threat of a diffusion flame anchored at the break may be less severe than conservative analysis would indicate. Furthermore, such a flame can remove hydrogen at the source and minimize the possibility of a global gas explosion.

Introduction

During a postulated loss-of-coolant accident in a CANDU® reactor, high-temperature hydrogen-steam mixtures emerging from a break in the reactor's primary heat transport system are released into the containment building and can accumulate to flammable concentrations. The ignition of the flammable mixture can result in a flash back and the formation of a turbulent diffusion flame at the break. Therefore, the creation of a diffusion flame at the break can be a direct outcome of the deliberate ignition scheme. It should be mentioned that a discrete ignition source is not always needed. The emerging mixture can also auto-ignite if its temperature is sufficiently high. For a dry hydrogen jet, the auto-ignition temperature was found to be about 680°C [1]. The effects of such a diffusion flame in the containment building are twofold. First, it can remove hydrogen (or deuterium) as it leaves the break, thus minimizing the potential of a global gas explosion inside the containment building. Second, the high thermal load from a diffusion flame can potentially threaten the survivability of nearby safety equipment. To fully assess the

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CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL) consequences of the deliberate ignition scheme, it is necessary to determine whether a stable diffusion flame can form at a break. If a flame does form, it is necessary to estimate the thermal load on nearby objects for various postulated accident scenarios. A general review on the structure and heat transfer of various types of diffusion flames relevant to a nuclear reactor accident were reported by Shepherd [2]. Most of the reported data were on vertical dry hydrogen flames. Data for non-vertical flames involving hydrogen-steam mixtures, particularly for mixtures with high steam content, were limited. This paper summarizes the results of a recent study performed at AECL Whiteshell Laboratories on the stability, structure and thermal load of non-vertical hydrogen-steam diffusion flames. The objective of this study is to determine the impact of a standing flame following a postulated nuclear reactor accident.

Experimental Facility

Experiments were performed in the Diffusion Flame Facility at Whiteshell Laboratories. A schematic of the facility is shown in Fig. 1. This facility consists of a 15-cm diameter burner mounted inside a modified grain silo (5 m in diameter, 8 m height). The burner and the silo were insulated such that experiments involving hydrogen-steam diffusion flames in air-steam environment can be performed. Various flame or jet structures can be created by mounting an orifice at the exit end of the burner. In this series of experiments, circular orifices with diameters of 6.35, 12.7 and 19.0 mm were used. The burner can also be tilted such that its orientation can be adjusted from horizontal to vertical. In this study, the burner was fixed at the horizontal position. Since experiments were performed in a confined space, the amount of hydrogen used in each experiment was limited to 2 m^3 for safety reasons. To ensure ignition of the gas mixture, two propane pilot flames located 20 cm and 50 cm from the burner were employed. The steam composition in the jet was varied from 0 to 90% by volume in this series of experiments. The jet velocities were varied from 50 to 500 m/s. Within this range of experimental parameters, both the Reynolds numbers and the Froude numbers were much larger than 1000, indicating that the structure of the flame was momentum-dominated. Video cameras and arrays of thermocouples were used as diagnostic tools. An array of 1.5-mm Cromel-Alumel thermocouples (spaced 15 cm apart) was mounted along the centerline of the burner to monitor the flame length and the flame temperature. Each test was recorded on video to assess the stability of the flame. A flame was considered to be unstable when video records showed that the flame was not anchored between the exit of the burner and the first pilot flame.

Ignition and Stability of Diffusion Flames

Ignition and stability of diffusion flames are, in essence, similar phenomena. They are both controlled by the same mechanism. Ignition of a jet of hydrogen-steam mixture will occur if the mixture is within the flammability limits and the temperature, along the combustible interface between the fuel and the surrounding air is high enough to cause auto-ignition. If the hot combustion products can continuously ignite the emerging mixture, a stabilized flame results. It was observed that, for a fixed jet composition and break configuration (shape and size), a stable diffusion flame can only anchor itself in the vicinity of the break if the flow rate is less than a certain critical value. Figure 2 shows the stability boundaries for three different orifice sizes. The experimental variables were steam composition in the jet and the jet velocity. It was observed that the destabilization of a diffusion flame occurs in two steps. These are referred to as lift-off and blow-out. As the velocity or the steam content of the jet is increased, the base of the flame (the start of the chemical reaction zone or the luminous zone) lifts off the burner and becomes fixed at some distance downstream. The distance between the burner and the base of the flame increases as the flow rate increases until the critical blow-off condition is reached. Beyond this critical condition, a flame cannot stabilize itself in the vicinity of the burner. For safety analysis, a lift-off flame is also regarded as a stable flame.

Results from this study show that the stability of the flame depends very strongly on the steam content in the jet, but is only mildly affected by the jet velocity. The effects on flame stability for a jet velocity being increased by one order of magnitude (from 50 to 500 m/s) are similar to an increase in steam concentration by 10 vol. %. Results also reveal that the stability is very sensitive to jet diameter. At a jet velocity of 200 m/s, the stability limit (expressed in terms of steam concentration in the jet) for orifice diameters of 6.35, 12.7 and 19.0 mm are 30, 30 and 70% respectively. This implies that diffusion flames are more stable for jets of larger diameters. Within the range of experimental conditions examined, no stable diffusion flame was observed for a hydrogen concentration in the jet less than 25% by volume. It should be pointed out that this limiting concentration depends on jet velocity. Shepherd [2] performed diffusion flame experiments with jet velocities lower than the range of velocities examined in the present series of experiments. He did not observe a stable diffusion flame for a hydrogen concentration less than 15% by volume. Depending on accident scenarios, the emerging fluid from a break in the primary heat transport system may have a hydrogen content higher than this limit value. If there is sufficient air in the atmosphere surrounding the break, a diffusion flame that anchors at the break is a possible outcome.

Flame Length

Classically, the flame length is defined as the distance between the burner and the point at which all of the jet fluid has mixed with the surrounding air and reacted [3]. Since most diffusion flames are unstable, flame lengths are difficult to measure accurately. Experimentally, they are obtained either by long-exposure photography or by temperature measurement along the centerline. In the former method, the length of the luminous region is taken as the flame length. A reference temperature needs to be defined in the latter method. Usually this reference temperature is chosen arbitrarily. Flame length, although not well defined, is of great significance to reactor safety analysis. Along the flame surface, the temperature can be conservatively assumed to be approximately equal to the constant pressure combustion temperature for stoichiometric hydrogen-steam-air mixtures. Depending on the steam content, this temperature can be as high as 2000°C.

For horizontal jet flames, buoyancy effects created by the hot combustion products can cause a flame to bend up. Depending on the momentum of the jet fluid, buoyancy can significantly reduce the flame length. To quantify the potential hazard of these flames, the penetration depth is a more meaningful parameter to measure than the physical length of the flame. The penetration depth, L_p, for horizontal hydrogen-steam diffusion flames was measured for various jet steam concentrations and jet velocities. In this series of experiment, both the "photographic" method and the "reference temperature" method were used. Results are summarized in Fig. 3 and Fig. 4. To determine the scale effect on the penetration depth, three different sizes of jet diameters were examined. Figure 3 shows the penetration depth for dry hydrogen diffusion flames of various jet velocities. Results based on two different reference temperatures, 500 and 600°C, are compared to the results based on video records. In general, a higher reference temperature yielded a shorter penetration depth. Results also show that for a small diameter jet (D_j = 6.35 mm), the penetration depths determined using a video camera (solid circles) agreed well with those determined by temperature measurement (open circles). A reference temperature of 600°C was used. As the jet diameter increases, the two results differ significantly. For safety analysis, the temperature method would yield more meaningful results. Even though the penetration depth determined by the two methods are very different, they show similar trends. The penetration depth increases as the diameter of the jet increases. This trend agrees with the observation from an earlier experiment [1] on vertical diffusion flames. To examine the scale effects of hydrogen diffusion flames, the normalized penetration depths (L_p/D_j) for different orifices were compared with one another. For a jet velocity of 500 m/s (representing a choked flow at the orifice), the values of L_p/D_j (using a reference temperature of 600°C) for the 6.35, 12.7 and 19.0-mm diameter orifices were found to be 157, 95 and 79 respectively.

Many theories are available to predict flame lengths. Reviews of these theories can be found in reference [4] and [5]. For flames with high Froude numbers (momentum dominated), Hottel [6] and Dimptakis [7] found that the flame length can be expressed as the distance downstream at which a constant fraction of the entrained fluid has been mixed at the molecular level and has reacted with the original jet fluid. This observation seems to apply to all flames in which the reaction rates are sufficiently fast. Assuming that the entrainment rates for burning jets are the same as for non-reacting jets, flame lengths can be correlated as a function of jet parameters. It is found that the flame length (*L*) is linearly proportional to the product of the equivalence ratio, the square root of the density ratio and the jet exit diameter:

$$L = 10\phi\left(\frac{\rho_o}{\rho_\infty}\right)^{\frac{1}{2}} D_j$$

where ρ_0 and ρ_∞ are the densities of the jet and ambient fluid respectively and D_j is the diameter of the jet. The equivalence ratio ϕ is defined as the mass ratio of air to jet fluid in a stoichiometric mixture. For example, a pure hydrogen jet fluid into air has a value of ϕ equal to 35. The ratio L/D_j is estimated to be roughly 90. This estimate agrees reasonably well with experimental observation on vertical hydrocarbon and hydrogen diffusion flames. This simple theory seems to be able to provide a reasonable estimate of the penetration depth for horizontal hydrogen-steam diffusion flames also.

Figure 4 shows the effects of steam in the jet on the penetration depth. Results from this figure were determined using the photographic method. Nevertheless, the effects of steam are clearly shown. Steam content in the jet has a strong effect in reducing the penetration depth of the flame. Increasing steam content in the jet can render the flame unstable and lead to blow-off of the flame.

Flame Temperature

The primary threat from diffusion flames is the high thermal load imposed on nearby safety-related equipment. For a 1 kg/s hydrogen release rate, the diffusion flame can generate 120 MW of thermal power. A calculation of the rate of energy transfer between surfaces with surrounding hot gases is relatively straightforward if the temperature field is known. Knowing the thermal properties of the gas and the surface, the rate of energy transfer can be calculated using standard convective heat transfer equations available in reference texts [8,9]. The high thermal load usually results from direct impingement of the flame with the object [10]. Therefore, the most critical parameter in this calculation is the peak temperature in the flame. The peak flame temperatures were measured in the present series of experiments. Results are summarized in Fig. 5. For dry hydrogen diffusion flames (D_j = 12.7 and 19.0 mm), the peak temperatures along the centerline were measured to be about 1150°C. For small jet flames (D_j = 6.35 mm), the reaction zone is very localized and the thermocouple array in the facility does not have sufficient resolution to detect the peak flame temperature accurately. Nevertheless, the 1150°C is still much lower than the adiabatic constant pressure combustion temperature (~2000°C) of a stoichiometric hydrogen-air mixture. These results suggest that turbulent mixing with the surrounding cold air significantly reduces the temperature in the reaction zone. Furthermore, the peak temperature is found to be very sensitive to the mixture composition. The peak temperature decreases as the steam content in the jet increases. However, for high velocity jets, the peak temperature is not very sensitive to the variation in jet velocity.

In most nuclear reactor accident scenarios involving a break in the primary heat transport system, the emerging fluid will contain some steam. Based on the results from this study, the peak temperature is expected to be lower than 1000°C. This temperature is lower than the melting temperature of most metallic surfaces except aluminum. This implies that the safety equipment inside the containment building can be easily protected by shielding with sheet metal. It should be pointed out that this temperature is still higher than the melting temperature of most cable insulation. These results have implications in hydrogen management following a nuclear reactor accident. The threat of hydrogen-steam diffusion flames created by the deliberate ignition scheme requires consideration but may not be as severe as anticipated by the conservative, adiabatic constant pressure combustion assumption, using stoichiometric mixtures.

Conclusion

A systematic study on the stability and the structure of various horizontal hydrogen-steam diffusion flames was performed in the Diffusion Flame Facility at AECL Whiteshell Laboratories. Jet conditions similar to those of emerging fluid at a break in the primary heat transport system after a nuclear reactor accident were examined. It was observed that, for a certain range of hydrogen-steam compositions, a stable diffusion flame can exist and anchor itself at the break. Due to the presence of steam and turbulent mixing with the surrounding cold air, the peak flame temperature is much lower than the adiabatic constant pressure combustion temperature of a stoichiometric hydrogen-air mixture. These results suggest that the safety equipment inside the containment building can be protected by shielding with sheet metal. As a result, the threat of a diffusion flame anchored at the break may not be as severe as anticipated. Furthermore, such a flame can remove hydrogen at the source and significantly reduce the possibility of a global gas explosion.

Acknowledgment

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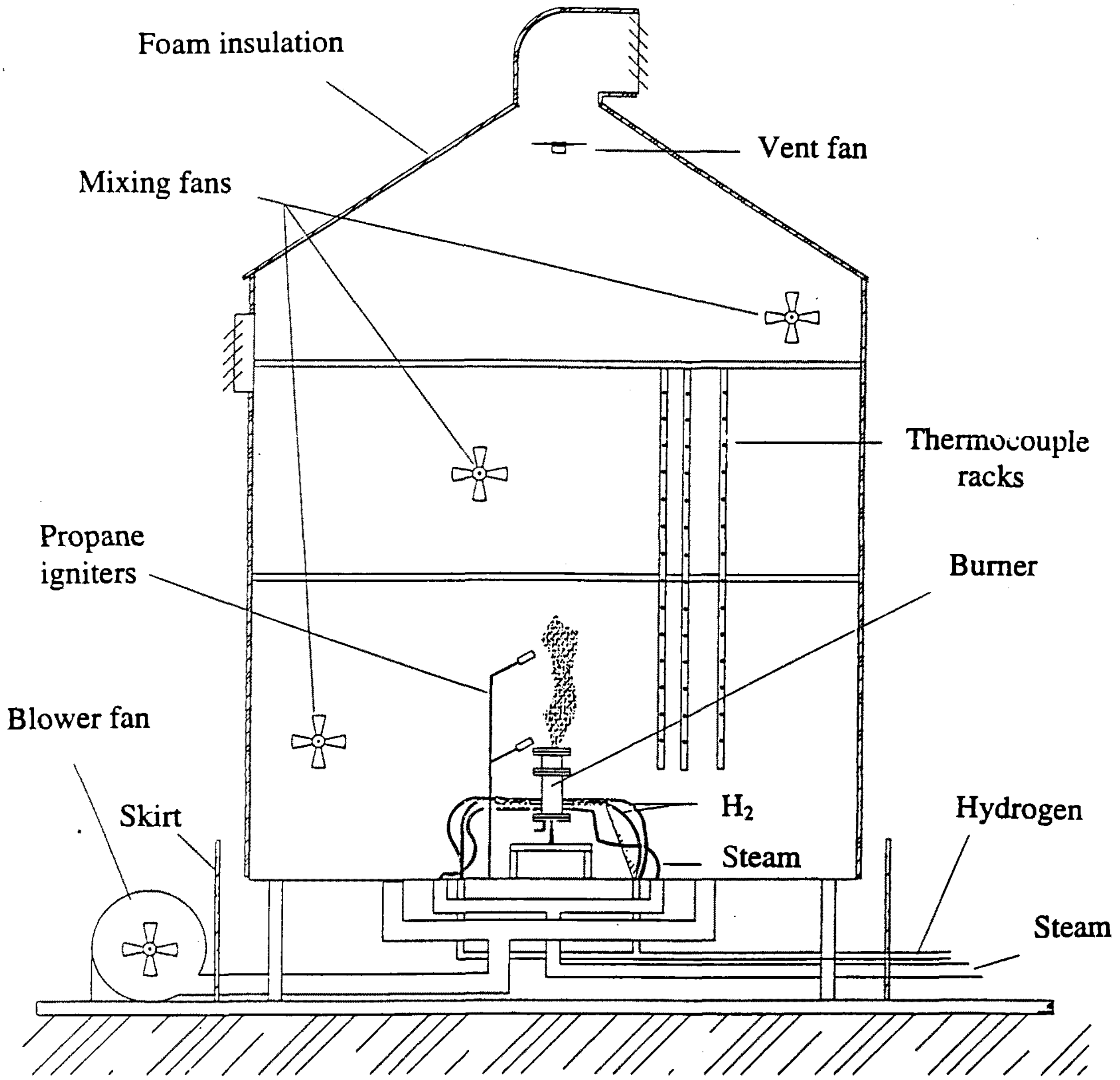

Figure 1. Schematic of the Diffusion Flame Facility.

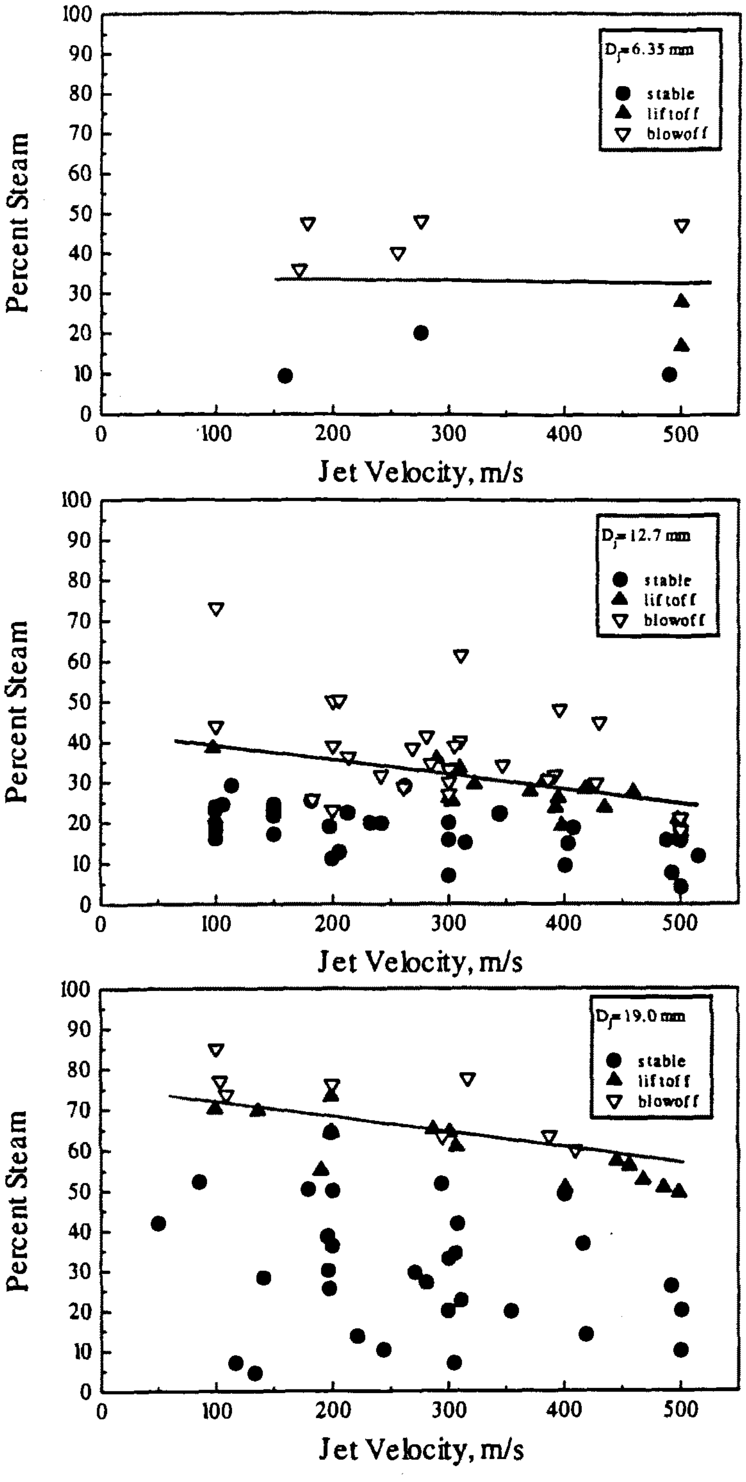

Figure 2. Stability Regimes for Various H_2-Steam Diffusion Flames
(50 m/s < V_j < 500 m/s, D_j = 6.35 mm, 12.7 mm and 19.0 mm).

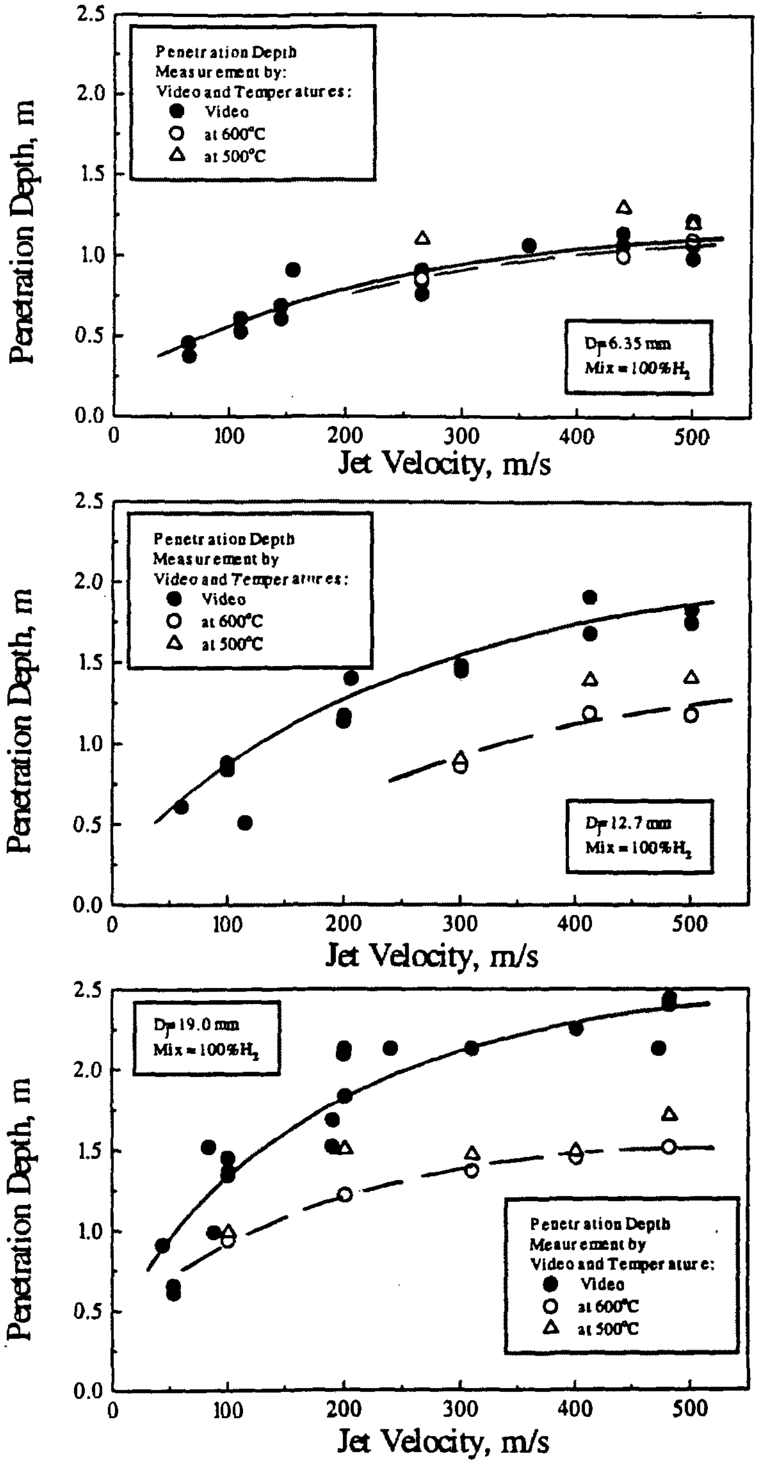

Figure 3. Penetration Depths of Various Dry H_2 Diffusion Flames (50 m/s < V_j < 500 m/s, D_j = 6.35 mm, 12.7 mm and 19.0 mm).

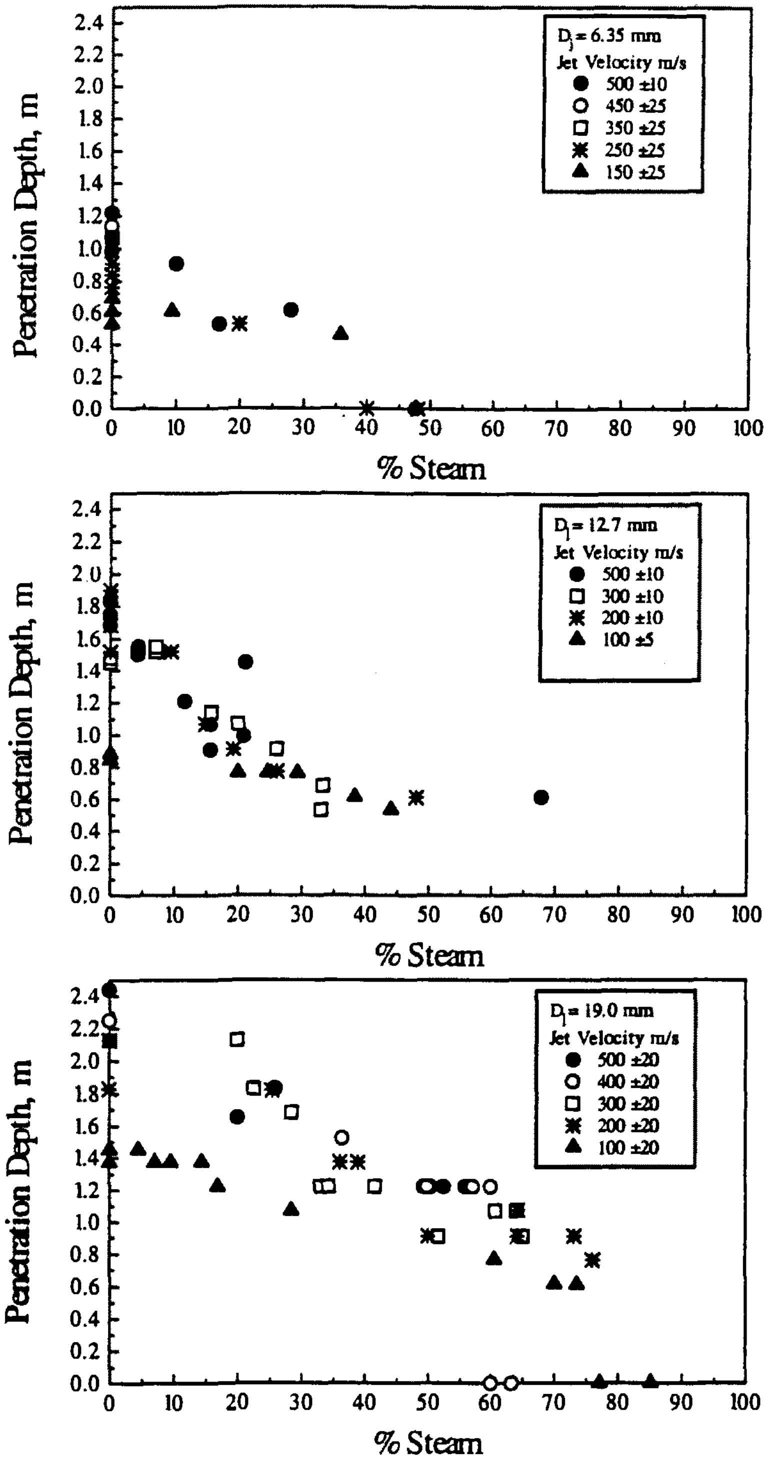

Figure 4. Penetration Depths of Various H_2-Steam Diffusion Flames.

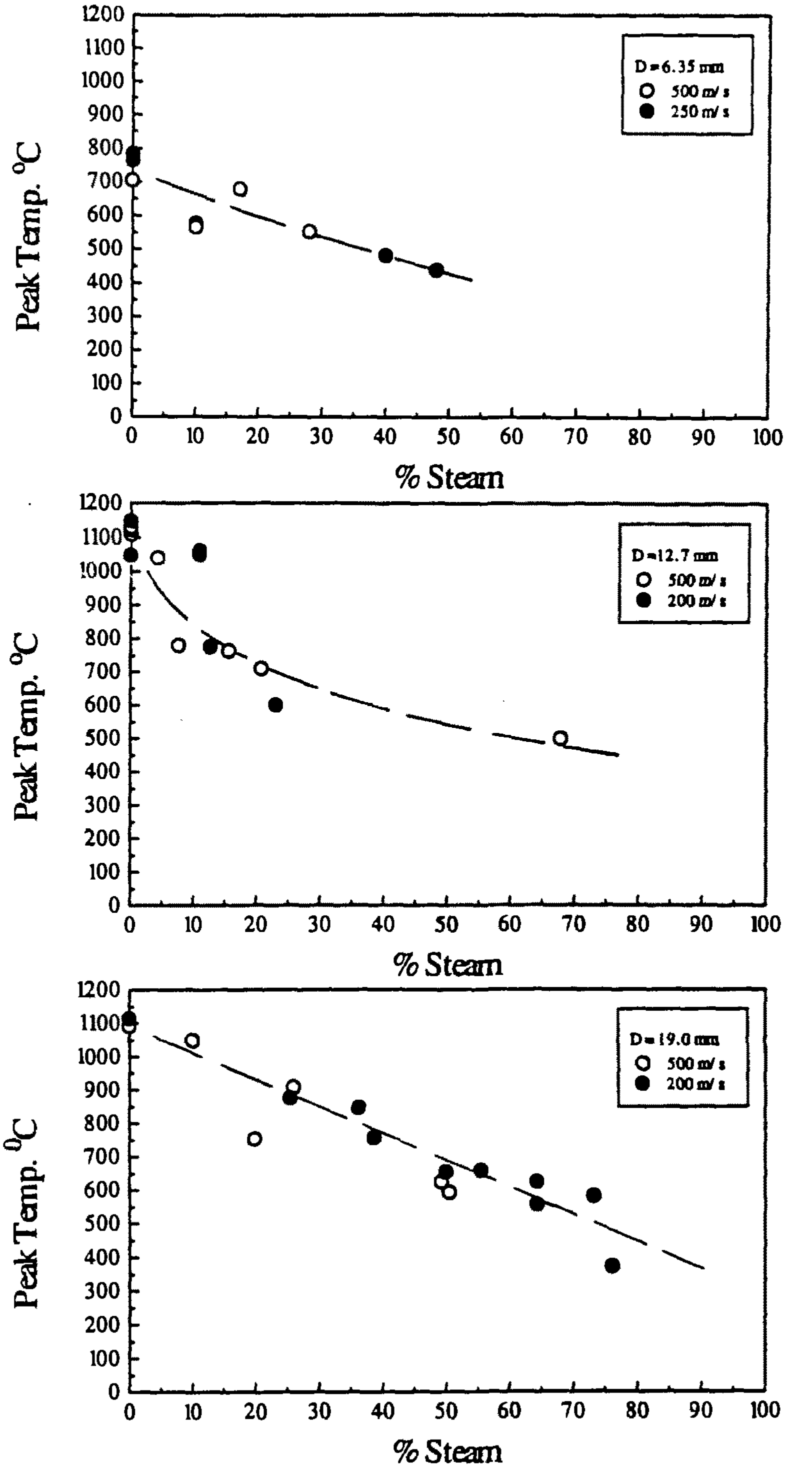

Figure 5. Peak Flame Temperatures of Various H_2-Steam Diffusion Flames.