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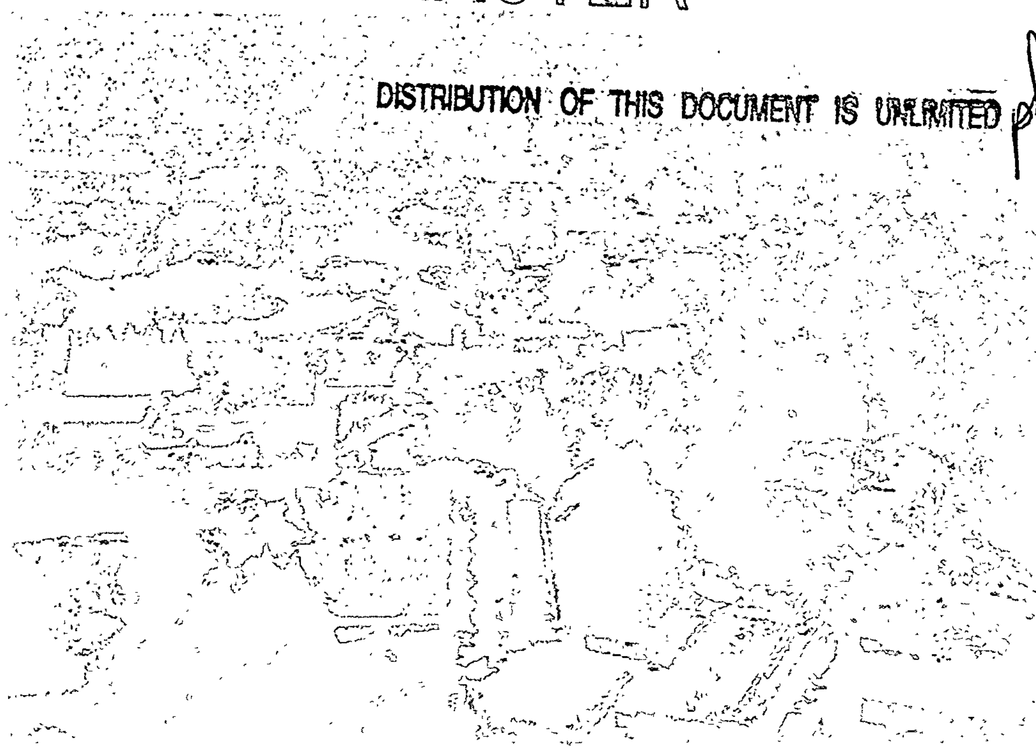

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ABSTRACT

This paper describes the continuing development of the Weak-Swirl Burner (WSB) for use in low NO_x applications. Weak-swirl is a unique method for stabilizing lean-burning, premixed combustion as the flame is stabilized by flow divergence, not through recirculation as is commonly seen in nonpremixed industrial burners. Earlier versions of the WSB used a tangential air jet swirler that offers flexibility for determining the range of operation and evaluating the performance of the WSB. Though common in large applications, air swirler may not be amenable to small and medium-size appliances. To reduce manufacturing costs and burner complexity, we have developed a fixed vane swirler to replace the air jet swirler in the WSB. This paper describes the operating characteristics and key design parameters of the vane swirler. A new expression for determining swirl number intensity is developed. Testing of a laboratory water heater fitted with a WSB with the new vane-swirler shows $0 < NO < 20$ ng/J, $10 < CO < 70$ ppm, and thermal efficiencies ≈ 78% over the lean burning range of $0.70 < \phi < 0.90$. The continuous firing rate is robust for a 53 mm vane-swirled WSB, with initial tests ranging from 40,000 to 400,000 Btu/hr. for $0.60 < \phi < 1.0$. Successful development of the new vane swirler demonstrates that the low emission WSB is adaptable to a wide variety of industrial applications.

INTRODUCTION

As a majority of water heaters operate with diffusion or partially premixed burners, nitrogen oxide (NO_x) levels are often greater than 50 nanograms of NO_x per Joule of heat output (ng/J). There is concern in the industry that stricter California regulations (possibly < 40 ng/J or less) will be unattainable by their current products without expensive pollution remediation strategies. An alternative to diffusion burners is to use premixed burners which have lower NO_x levels due to the lower flame temperatures of lean premixed combustion. Although premixed burners are currently offered, they have not penetrated a large sector of the market because they tend to be costlier and more difficult to scale than their counterparts. The objective of our research is to develop the premixed weak-swirl burner (WSB) for use in commercial applications. This burner was originally developed for fundamental research into turbulent combustion processes[1]. Its simplicity of design is conducive to producing a more economical, durable, and readily scaleable burner. The work described in this paper was performed as part of our collaboration with Teledyne Laars to assess the feasibility of utilizing the WSB in pool heaters. At the 1995 AFRC meeting, we presented a paper[2] that described the results of adapting a WSB to a laboratory demonstration model of a 60,000 Btu/hr. spa heater.

The WSB used for our previous studies relied on tangential air jets to inject swirl into the outer edges of the premixed flow (Fig. 1A). Air injection was chosen to allow easy control of the swirl rate. This flexibility was important for the initial phase of our research to demonstrate the feasibility of the WSB in a confinement typical of a pool heater. These air-swirled WSBs may be better suited for those applications where compressed air is already available and utilized, such as in boilers and industrial furnaces. Clearly, air injection would be impractical and uneconomical (due to the necessary compressor and controls) for high volume, low margin consumer products such as pool heaters. Thus, an important milestone in the our collaborative project is to replace the air swirler with a simple and economical vane-swirler which could produce the necessary flow field to stabilize the flame. Reported here is our development of this new vane-swirler designed specifically for use in the WSB. As the function of this swirler is to generate divergent flows for flame stabilization, a new formulation for the swirl number is developed to characterize swirl intensity and for potential future use as a design tool in scaling the WSB to other applications. Also reported are emission and efficiency results when the vane-swirled WSB is tested in a laboratory system that simulates the operation of a 60,00 Btu/hr. spa heater.

CONVENTIONAL SWIRLER DESIGNS

Swirling flows have been used for stabilizing nonpremixed and premixed combustion for decades in combustion systems such as turbines, industrial coal burners, and gas furnaces. Due to the impact of swirl in pollutant formation, combustion efficiency, combustion stability, fluid dynamics, and flowfield generation, swirling flows have been subjects of both basic and applied research that have been reported in many journals, review articles,[3,4] and book chapters[5]. The majority of these articles focus on nonpremixed flames. This is reasonable, as commercial burners generally utilize a physical configuration where fuel (either gaseous, liquid droplets/spray, or solid particles) is injected into the chamber through a round orifice, with air being introduced to the system through an annular region surrounding the central fuel rod. Swirl is imparted to the system by either swirling the coaxial air flow or by injecting the entire flow tangentially into a cylindrical chamber as in cyclone combustion chambers. In both cases, the function of the swirl is to create a toroidal recirculation zone (TRZ). The TRZ is fundamental to these burners as it quickly mixes the fuel and air to allow for complete combustion, lengthens the residence time of the products, stabilizes the combustion process, and dictates the physical shape and length of the flame.

The non-dimensional swirl number, S, is a common parameter for characterizing swirl intensity. It is define as the ratio of axial flux of angular momentum to the axial flux of linear momentum divided by nozzle radius[5]:

$$S = \int_0^R UWr\,dr \Big/ R\int_0^R U^2 r\,dr \qquad (1)$$

where R is the nozzle radius, and U and W are the mean axial and tangential components of the flow velocity within the swirl generator. The integral form of Eq. (1) assumes symmetry around the central axis and local velocity measurements are needed for an accurate determination of S.

Two classical configurations to generate swirl are tangential air injection and angled guide vanes mounted radially on a central hub. In our earlier paper[2] with tangential air injection, it was convenient to use the geometric swirl number:

$$S_g = \frac{\pi r_\theta R}{A_\theta}\left(m_\theta/\left(m_\theta + m_a\right)\right)^2 \tag{2a}$$

As Eq. (2a) is only good for tangential injection, Eq. (1) must be used for the case of a vane swirler with a central hub radius of R_h. Assuming U is uniform over the tube cross section, integrating from R_h to R reduces Eq. (1) to;

$$S = \frac{2}{3}U^2 \tan\alpha\left(R^3 - R_h^3\right)/RU^2\left(R^2 - R_h^2\right) \Rightarrow \frac{2}{3}\tan\alpha\,\frac{1-\left(R_h/R\right)^3}{1-\left(R_h/R\right)^2} \tag{2b}$$

with α defined as the vane angle from the vertical axis. Equation (2b) is easier to apply in engineering design than Eq. (1) as it is based on the physical geometry of the vane swirler rather than on momentum flow rates. The emphasis of the conventional hub vane-swirler design is to generate a TRZ by exploiting the hub as a bluff-body. TRZs are formed only when there is a high degree of swirl in the flow field, with recirculation beginning at $S \geq 0.6$. Almost all information in the scientific literature on swirl flame stabilization has focused in the regime of $S > 0.6$.

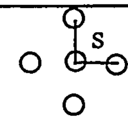
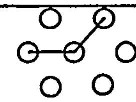
The swirl requirement of the WSB is different from much of the previous research as the burner is premixed and flame stabilization is achieved through the use of a divergent flow field instead of a TRZ. Due to the propagating nature of premixed flames, the decelerating flowfield allows the flame to dynamically stabilize itself at the position where the local flow velocity equals the flame speed. The weak-swirl stabilization mechanism does not apply to diffusion flames because they doe not propagate but burn at the boundary where the air and fuel flows have been mixed and diffused to the appropriate ratios for sustaining the combustion reaction.

It is obvious that the conventional hub vane-swirler design is not appropriate as recirculation is undesirable in the WSB. For their investigation of scalar dissipation in premixed turbulent flames, O'Young and Bilger[6] modified our WSB design by replacing the air injectors with an outer vane-swirler to generate swirl. This burner requires separate control of the premixture and swirl air and does not meet our criterion of a simple design. Our goal is to develop a vane-swirler that operates with a single flow control and supply. Extensive experimentation led us to the design shown in Figure 1B. The key feature that distinguishes our new vane-swirler from a conventional hub swirler is that it has a center open tube through which some of the premixture is allowed to pass. Though, similar swirler configuration has been used in a study of the effects of upstream swirl on flame oscillations[7] such a design has yet to be exploited for premixed flame stabilization. With the correct balance of core and annular flow, this vane-swirler produce the divergent flow necessary for stabilizing lean premixed combustion. As the photographs show in Figure 1, general flame features are the same as those produced by the air-jet swirler.

EXPERIMENTAL APPARATUS AND DIAGNOSTICS

Figure 1(B) contains a schematic of the burner configuration used for all the experiments presented in this paper. The vane-swirler splits a single supply of premixed natural-gas/air into an inner tube ($R_h = 20.5$ mm, length = 35 mm), and the outer annulus ($R = 26.4$ mm) where $R_h/R = 0.776$ is fixed for all experiments. Eight guide vanes, with a fixed $\alpha = 37°$, impart tangential velocity to the flow in the annulus. The core and swirl flows interact as they leave the swirler section and travel downstream through a tube of length ℓ before exiting from the nozzle. The novelty of our vane-swirler is the use of screens with different amounts of blockage to correctly proportion the core and swirl flows in order to achieve flame stabilization without flame holders. Details of the four screens used for the measurements are shown in Table I.

Table I: Screens for inner tube

Screen	Blockage	Hole diameter	Hole to hole distance, s	Spacing of holes
1	75%	2.9 mm	5.1 mm (square)	
2	70%	3.2 mm	5.1 mm (square)	
3	65%	3.2 mm	4.8 mm (square)	
4	60%	3.2 mm	4.8 mm (hexagon)	

To interrogate the flow field generated by the vane swirler, velocity measurements were obtained by a two component Laser Doppler anemometry (LDA) system[1]. It uses a two color argon ion laser separated into four intersecting beams. Differential frequencies of 5 Mhz and 2 Mhz as generated by Bragg cells were used to remove directional ambiguity for the axial and tangential components respectively. Velocity traverses at 5 mm above the burner exit tube were used as the basis for comparing the flowfields generated by the vane-swirler and by the air-swirler. The laboratory test station used to evaluate the performance of vane-swirled WSB in conjunction with the simulated spa heater is described in detail in Ref. 2.

RESULTS:

Redefining the swirl number

The major difference between our vane-swirler and the conventional hub swirler is that our design allows for a center core of premixture which has no tangential velocity. Without a screen to distribute the flow to the annulus, the obvious consequence of this design would be to force most of the flow through the center core due to the higher pressure drop associated with the annular guide-vane section.. The use of screens with different blockages to balance the pressure across center and annular regions enables us to vary the swirl rate. Starting from Equation (1), S for the new geometry should be:

$$S = \int_0^R UWrdr \Bigg/ R\left(\int_{R_h}^{R} U^2 rdr + \int_0^{R_h} U^2 rdr\right)$$

which reduces to:

$$S_v = \frac{2}{3}\tan\alpha \frac{1-(R_h/R)^3}{1+(R_h/R)^2\left((U_c/U_a)^2-1\right)} \tag{3}$$

where U_c is the mean axial core velocity from 0 to R_h, and U_a is the mean axial velocity component in the outer annulus. The main assumption is that velocity is uniform within the core and within the annulus. However, U_c and U_a are not necessarily identical as they are affected by the screen blockage in the inner tube.

Figure 2 shows the functional dependence of S_v on the two important parameters, U_c/U_a and R_h/R for a vane-swirler with $\alpha = 37^o$. As S_v scales by tan(α), the general shapes of these curves remains the same for different α. These curves show that the proper limits are achieved by our definition of S_v. At $R_h \approx R$, i.e. tube flow without swirl, S_v reduces to zero, and when $U_c = 0$ as in the case of a solid hub, S_v is identical to Eq. (2). Figure 2 also shows that varying R_h/R of the hub swirler (solid line) from 0 to 0.9 only changes S by 50%. Note that Eq. (2) becomes meaningless at the limit of R_h/R = 1.0. For our new design where core flow is allowed, S_v can be conveniently varied by changing U_c/U_a or R_h/R. To seek a vane-swirler that works with the WSB, it was more convenient to vary U_c/U_a by fitting the inner tube with screens with differing amounts of blockage than by varying R_h/R because new fins would need to be fabricated for different R_h. Increased blockage increase S_v because the higher pressure drop through the inner tube forces more flow through the annular region. As shall be discussed later, once the regime of S_v for flame stabilization has been established for different velocities and equivalence ratios, the phase plane of Figure 2 would be useful as a design tool for scaling the WSB to different power ratings and physical dimensions.

LDA Measurement of Non-reacting flows

Experimental test conditions of a vane swirler with $\alpha = 37°$ and $R_h / R = 0.776$ are marked by symbols (+) on Figure 2. They include the four screens of Table I, the open tube (no screen) case and the closed tube (hub) case. All velocity profiles were obtained at 5 mm above the burner tube. The definition of S_v in its present form requires empirical input for U_c and U_a. Our approach is us an averaged velocity from r = -20.5 to r = +20.5 mm as U_c. U_a was then calculated from the mass flow rate of the total flow

$$U_a = (U_{inf}*R^2 - U_c*R_h^2)/(R^2 - R_h^2) \quad (4)$$

Here, U_{inf} is the mean flow velocity deduced from the total flow rate measured by a turbine flow meter.

Figure 3 shows the U profiles of the six conditions. With U_{inf} held constant at 3.0 m/s, the results indicate swirl numbers ranging from $0.27 < S_v < 0.58$ for the screens, $S_v = 0.03$ for the open case, and $S_v = 0.67$ for hub case. These U profiles are characterized by a uniform core flow region from -16 mm < r < 16 mm surrounded by the swirled region where the flow velocity can be higher or lower than the core region depending on the amount of center blockage. As expected, when there is no screen, restriction in the annulus region forces the bulk of the flow to accelerate through the inner tube, resulting in U_c much greater than $U_{inf.}$ At the other extreme, with complete blockage of the inner tube, U_c is negative, indicating that a recirculation zone has been generated downstream of the bluff body hub. This is in accord with the criterion that recirculation occurs when $S \geq 0.6$. For a 60% blockage, acceleration beyond U_{inf} still occurs as U_c is higher than $U_{inf} = 3.0$ m/s. Further increases in blockage force more flow into the annulus such that $U_c < U_{inf}$. With a blockage of 70%, U_c/U_a reduces to 0.5 and the calculated $S_v = 0.48$. Increasing the blockage further, to 75%, creates a situation where recirculation is imminent ($S_v = 0.57$). As this is undesirable for the WSB stabilization mechanism, increasing the blockage further was deemed unnecessary.

The results of Figure 3 show that blockage of above 65% but less than 75% would be appropriate for use in WSB. Compared in Figure 4 are isothermal velocity profiles generated by the earlier air-swirler and by our new vane-swirler with 65% blockage. The divergent flowfield produced by the air-swirler under this condition is known to support lean premixed flames. It can be seen that the vane-swirler produces essentially the same flowfield as that of the air-swirler. The mean tangential velocity profiles show two distinct regions; an inner core where there is no tangential velocity component W, and an outer annulus where W is present. U remains fairly constant across both profiles until dropping off toward the end of the flow region.

As S_v is dependent on the ratio U_c/U_a, and not sensitive to flow rate, it is not sensitive to U, varying U_{inf} rate should not affect S_v. Figure 5 shows U profiles for three cases with increasing U_{inf} (3.0, 5.0, and 7.0 m/s) for a 37 degree swirler with a blockage of 65% in the inner tube. The measurements here were taken without the use of an exit tube ($\ell = 0$ cm). As expected, the U profiles for the three mean velocities have the same shape, even duplicating the deficit at R_h. Calculating S_v shows some variance with U_{inf}, but no consistent trend is observed.

Operation of Burner with Vane-swirler

Of course, the most important issue is how does the vane-swirler perform in WSB. This was evaluated by determining the flame stabilization limits of burners with exit tube $\ell = 7$ cm, fitted with a 37° vane-swirler and different screen blockages. The flow supply and monitoring system for the burner is identical to that described in Yegian and Cheng[2]. Firing rate and ϕ are determined by two turbine meters measuring separate natural gas and air flow rates, and the WSB was operated open to the atmosphere. Figure 6 show the stable operating range for the four different screen blockages; 60%, 65%, 70%, and 75%. To obtain the conditions at blowoff and flashback, U_{inf} was held constant while the ϕ was varied. This resulted in the upper dotted lines which represent the flashback limit for each screen, and the lower solid line that denotes the blowoff limit. The regions between the two limits are where we found stable operation. For each of the four screens, the blowoff limits remain rather independent of U_{inf}. There is a general lowering of ϕ at blowoff with increasing blockage. At blockage of 60%, blowoff occurs at $\phi \approx 0.70$, while it lowers to $\phi \approx 0.55$ for a screen blockage of 75%. As expected, flashback limits increased with increasing U_{inf} as the flow velocity becomes significantly higher than the flame speed. For all cases, the data trends indicate that the flashback limit would be beyond $\phi = 1.0$ around $U_{inf} \approx 3.5 - 3.75$ m/s. As the maximum natural-gas/air flame speed occurs at $\phi \approx 1.0$, these results suggest flashback should not be a problem for operating conditions with $U_{inf} > 3.75$ m/s. Thus, the vane-swirler offers a wide operating range from stoichiometric through the lean regime and down to the blowoff limit. Although our results show that screens with high blockage have a broader operating range, we also observed that for blockages > 70%, the flame begins to change into an inverted cone where the apex may be situated within the exit tube. To produce the flat, disk-shaped flame that delivers even heat to a typical fin-and-tube heat exchanger found in pool heaters, a blockage of 65% seems to be optimum.

As stated earlier, commercial interest in the WSB, either air-swirled or vane-swirled, stems from its capability to stabilize lean ($\phi < 1.0$), premixed flames so that NO_x emissions can be lowered. Regulations are already in place within California restricting NO_x emissions to 40 nanograms of NO_x per Joule (ng/J) of useful heat output for water heaters (< 75,000 Btu/hr)[8] and self-contained space heaters (< 175,000 Btu/hr)[9]. It is not unlikely that these regulations will be expanded to other firing rates and appliances in the future. As NO_x generation is strongly dependent on temperature, lean flames are desirable as they have lower flame temperatures than the partially-premixed flames generated by conventional rack burners. To evaluate the performance of the vane-swirler in a practical situation, we used the laboratory test station (described in our earlier work[2]) that simulates the operation of a 60,000 Btu/hr Telstar spa heater.

Figure 7 compares NO and CO emissions, as well as thermal efficiency of the heat exchanger, for both the air and vane-swirled WSB. Note that the CO readings are in ppm while NO readings are in ng/J. This was done as NO_x and CO regulations are written in those different units. NO emissions are essentially the same for the air and the vane-swirled WSBs, ranging from 1 ng/J at $\phi = 0.70$ to about 17.5 ng/J at $\phi = 0.95$. Of particular significance is that these emission levels are well below the 40 ng/J regulation limit. When operated with its conventional partially premixed burner, the Telstar unit produces approximately 70 ng/J of NO, an order of magnitude higher than the WSB emissions.

As current regulations for CO are set at 400 ppm, it is seen that both the air-swirled and the vane-swirled WSB fall below these limits. A difference is found between the CO emissions for the two WSBs, with the air-swirler consistently producing at least double the amount of CO as the vane-swirler generates. The likely cause is incomplete combustion at the mixing region between the premixture and the swirling air where dilution may reduce the local stoichiometry below the flammability limit. The vane swirler does not encounter such a problem as both the core flow and the swirling annular flow are supplied by the same fuel/air source at a fixed ϕ. CO emissions of the vane-swirled WSB range from a high of 56 ppm at $\phi = 0.85$, to a minimum of 12 ppm around $\phi = 0.75$ before rising again at lower ϕ. As the thermal efficiency of the system does not appear to be compromised when $\phi \geq 0.75$, the CO "valley" and the corresponding NO emissions is used as the ideal operating conditions for the prototype WSB.

Due to fuel supply constraints, the laboratory experiments were limited to a maximum of 90,000 Btu/hr. Further tests have been completed at Teledyne Laars' testing facilities in Moorpark, California to find the maximum operating range for the 53 mm diameter WSB. Instead of fitting the swirler with our customized screens, the vane-swirler tested at Teledyne Laars used wire mesh screen and metal foam sheets. These materials are more easily available then our screens and do not increase production cost. The vane-swirler was found to operate reliably from 40,000 to 400,000 Btu/hr in the open, with ϕ ranging from 0.6 to 1.0. However, it should be emphasized that 400,00 Btu/hr is not highest possible firing rate of the WSB. Rather, it only represents the maximum currently achieved, as tests at Teledyne Laars were limited by the air supply system. When operating in a prototype heat exchanger at 250,000 Btu/hr, CO levels were comparable to those in Figure 7. The work completed at Teledyne Laars demonstrated the feasibility of operating a single size vane-swirled WSB at higher power ranges for a variety of units.

Future Plans

Although the scope of this work is limited to conditions of interest to developing water heaters, our results implies that vane-swirled WSBs can be adopted for use in many practical applications. More testing will be performed using different geometries (R, R_h, α, and vane length) and flow velocities (U_{inf}, U_c, and U_a) to characterize the stable operating range of the vane-swirled WSB versus ϕ and firing rates. These studies will show if the operating range of vane-swirler with different geometries fall within a narrow range of S_v. One these operational range are defined, it might be possible to express the operation range, through the use of the S_v expression, in terms of a blockage parameter instead of an empirical ratio U_c/U_a. This would enable a burner engineer to design a vane-swirler based strictly on the physical parameters of the swirler geometry to operate at the ideal condition of $\phi = 0.75 - 0.80$.

CONCLUSION

Our results illustrate the successful development of an economical and simple vane-swirler that can replace the air-swirler used in previous versions of the Weak-Swirl Burner. The vane-swirler produces the necessary diverging flow field to stabilize a lean premixed flame above the exit of the burner tube. The unique feature of our vane-swirler is a center tube that allows a portion of the premixture to pass through without being affected by swirl vanes fitted in the annular region. The center tube is the key element in generating the necessary flow divergence for stabilization by a WSB. This design differs from conventional vane-swirlers that emphasize the generation of recirculation zones. The vane swirler helps to simplify the design of WSB because is does not require two separate flow controls. A new expression was developed that takes into account the contribution of the flow momentum from the undisturbed core flow. In terms of performance, the WSB using a vane-swirler improves CO emissions while achieving the same thermal efficiency and low NO emissions. At the optimum operating condition of $\phi = 0.80$ (achievable by the four screens shown in Figure 6), NO emissions are less than a fifth of the proposed regulation limits of 40 μg/J, CO is a tenth of the 400 ppm limit, and thermal efficiency is uncompromised. With the successful development of a vane swirler to replace the air-injected swirler, an important milestone has been reached in the commercialization of an economical, durable, and reliable premixed weak-swirl burner.

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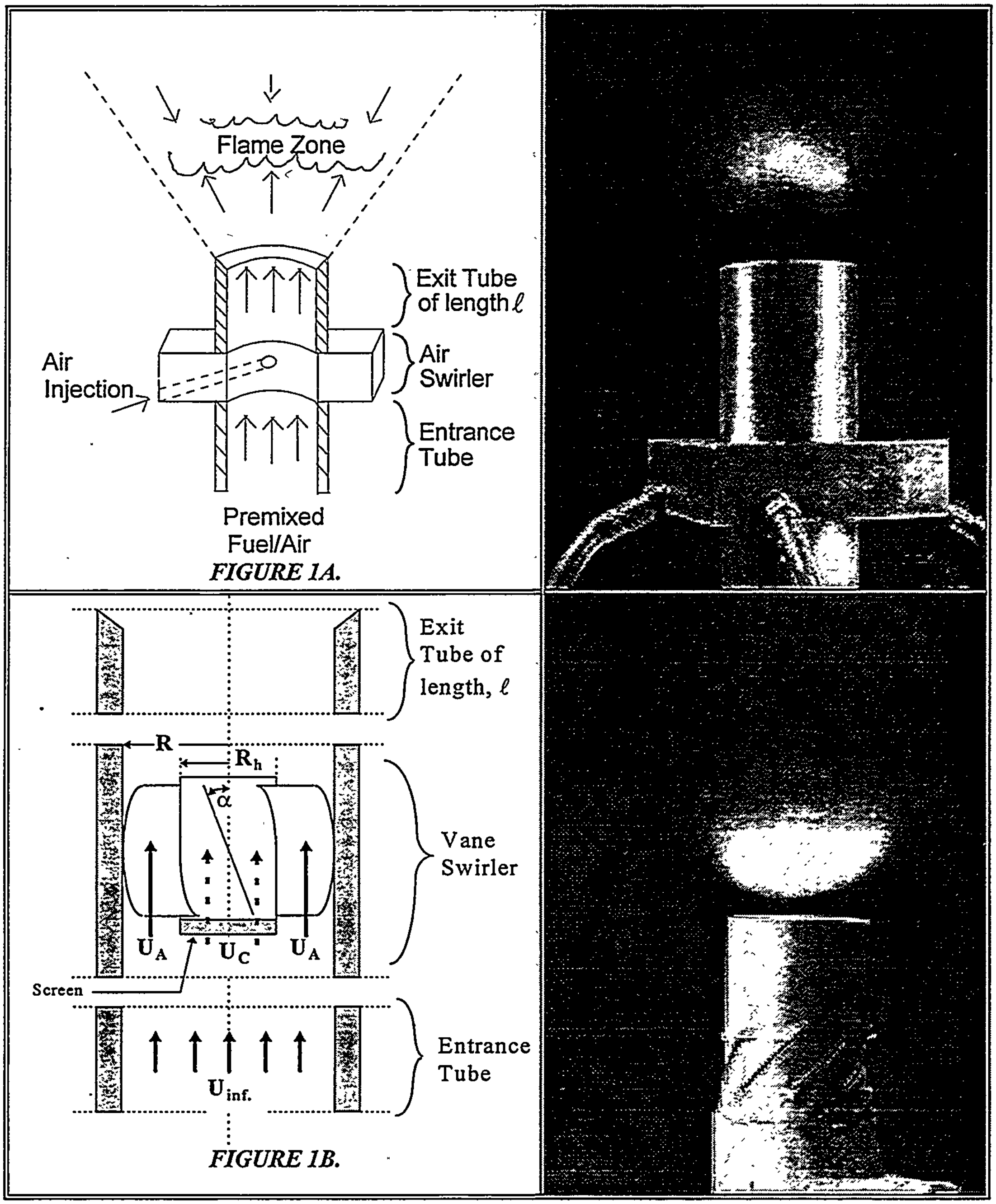

Figure 1: Schematics of the air-swirled WSB (Figure 1A) and vane-swirled WSB (1B) and representative flames. Note: Flame is detached from the burner tube in both cases.

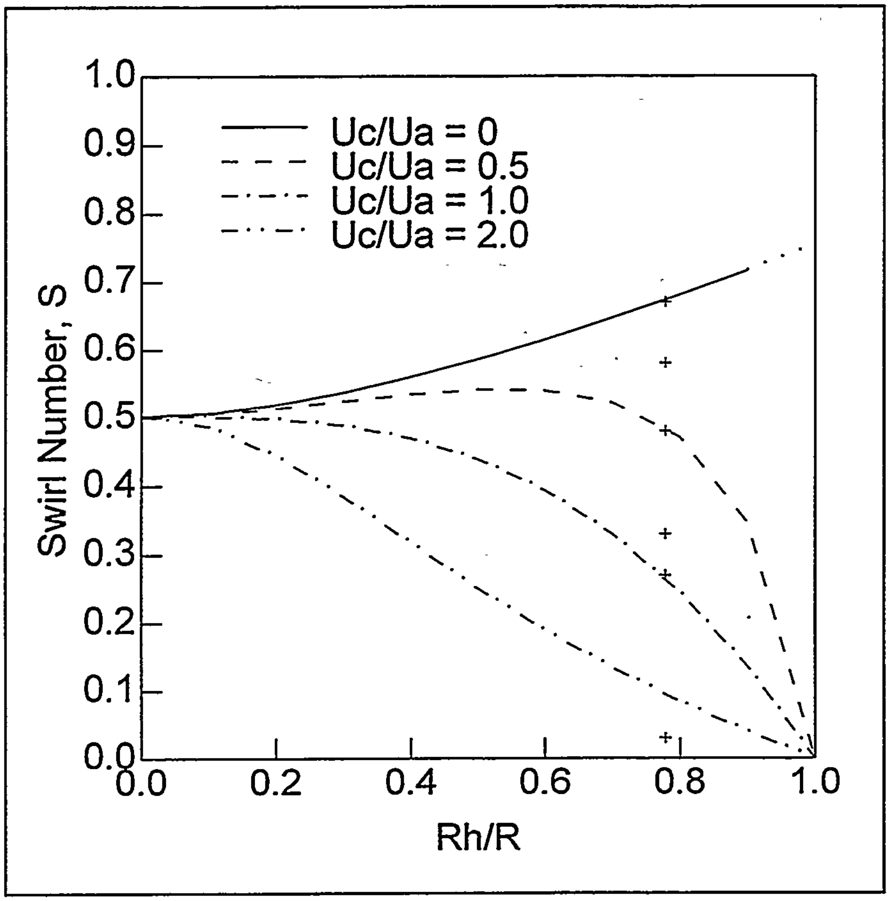

Figure 2: Functional dependence of S_v on R_h/R and U_c/U_a according to Eq. (2). Symbols mark the experimental points using the screens from Table I and the fixed R_h/R of 0.776.

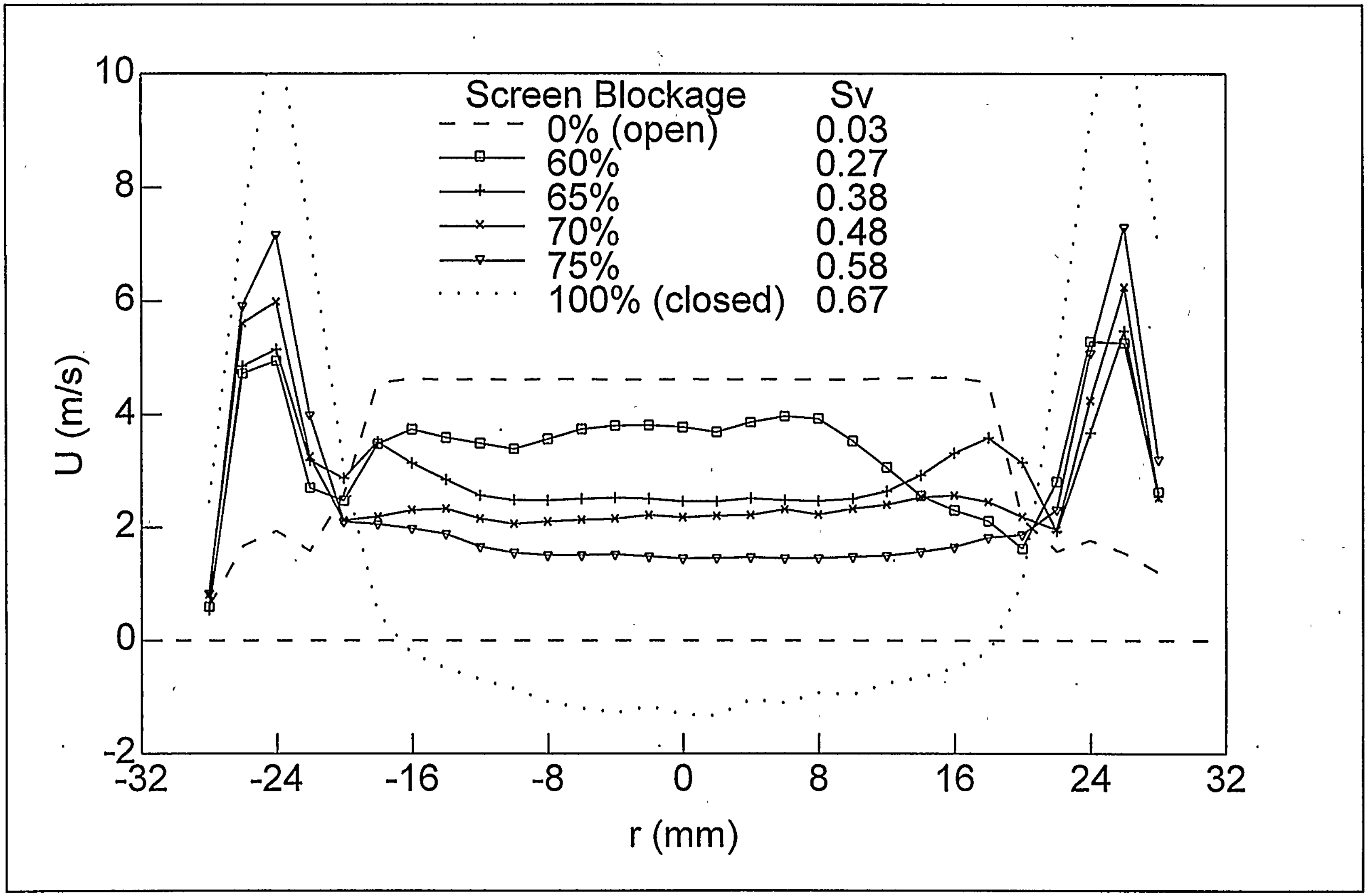

Figure 3: U profiles (U_{inf}= 3.0 m/s) for screen blockages varying from 0% to 100% (recirculation present).

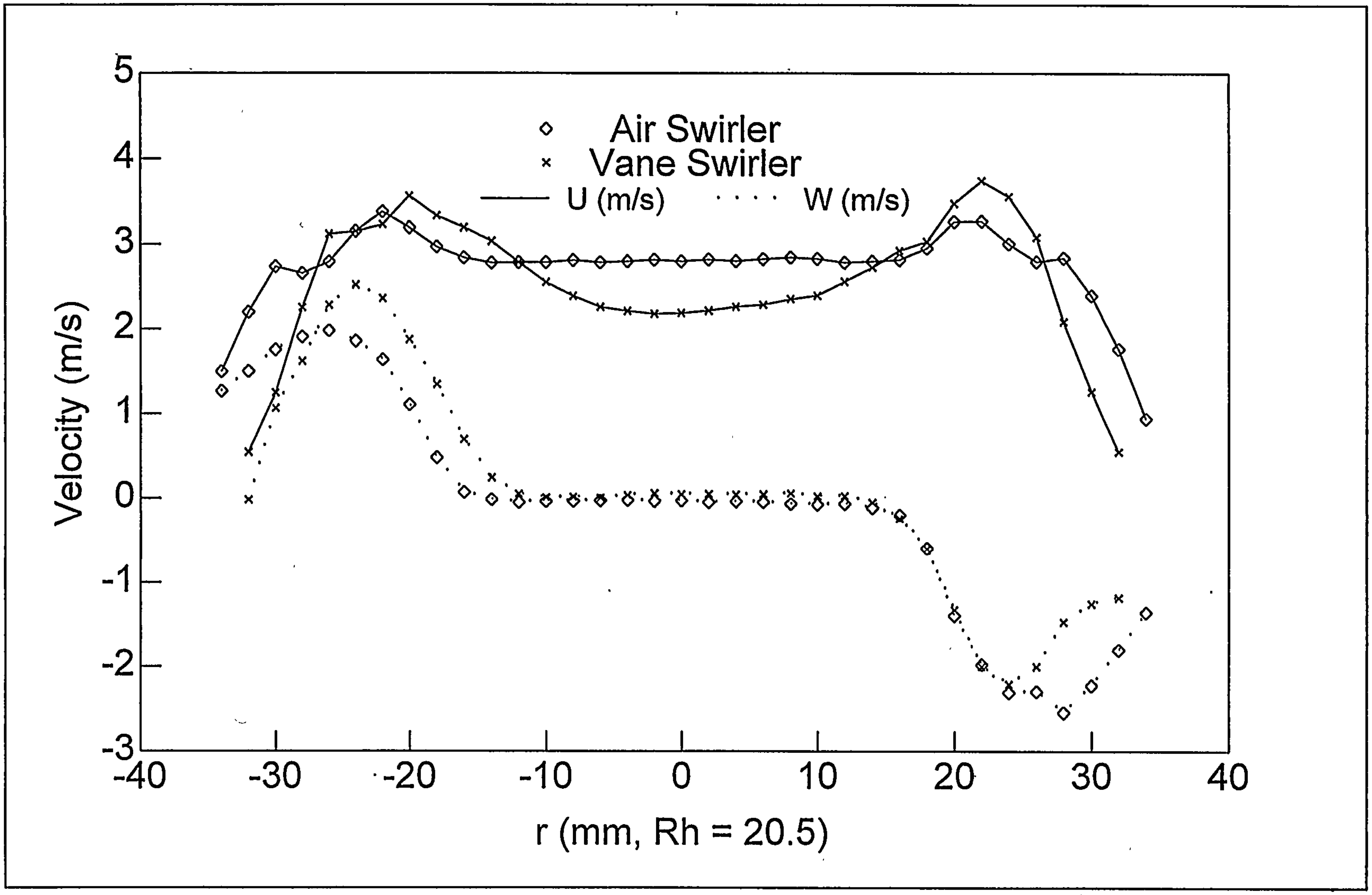

Figure 4: U,W velocity profiles (U_{inf} = 3.0 m/s) for an air-swirler and a vane-swirler (α=37°, 65% blockage) taken 5 mm above the exit rim (ℓ = 6 cm).

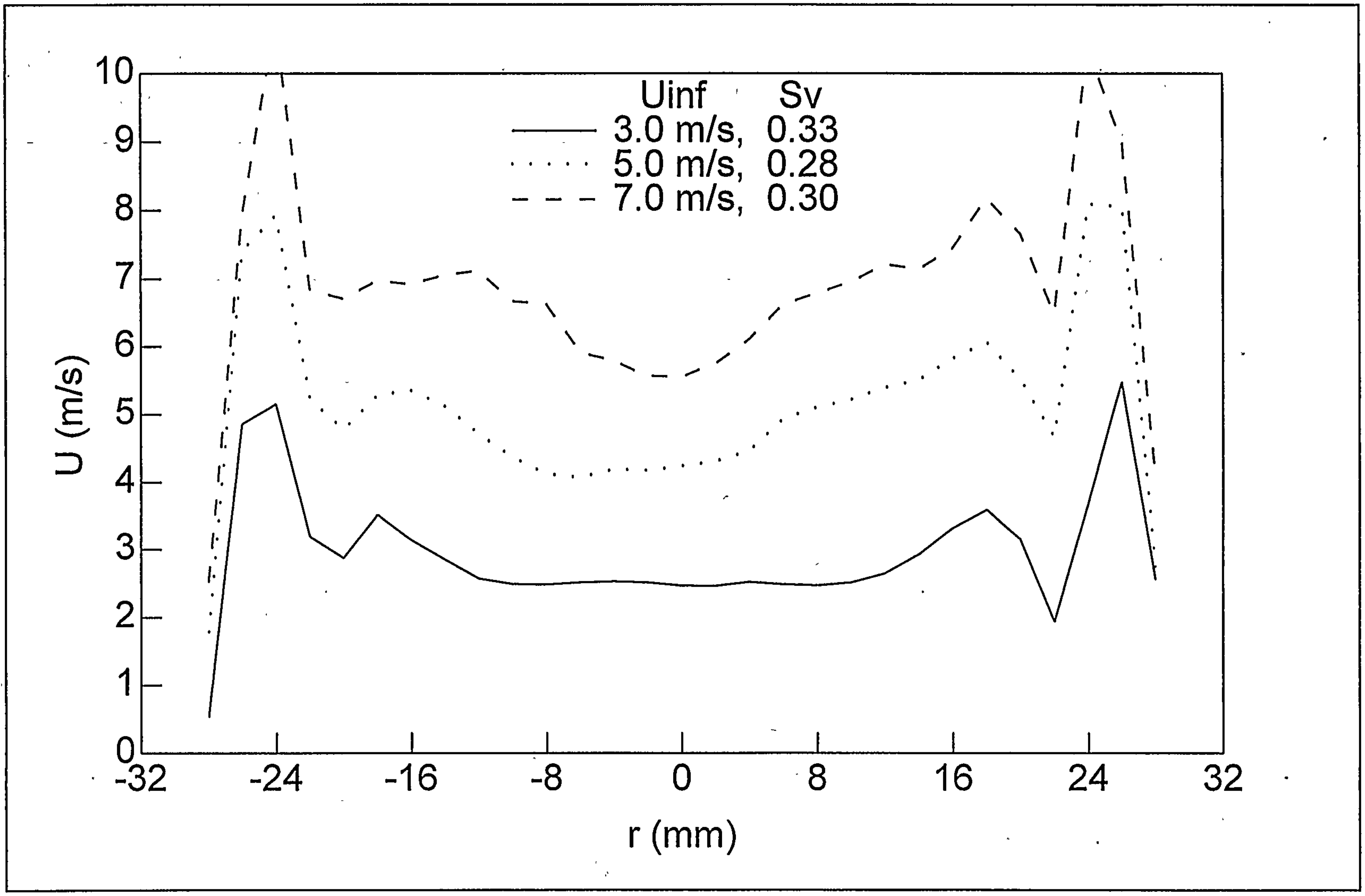

Figure 5: S_v remains similar for various U_{inf} for the vane swirler (α=37°, 65% blockage).

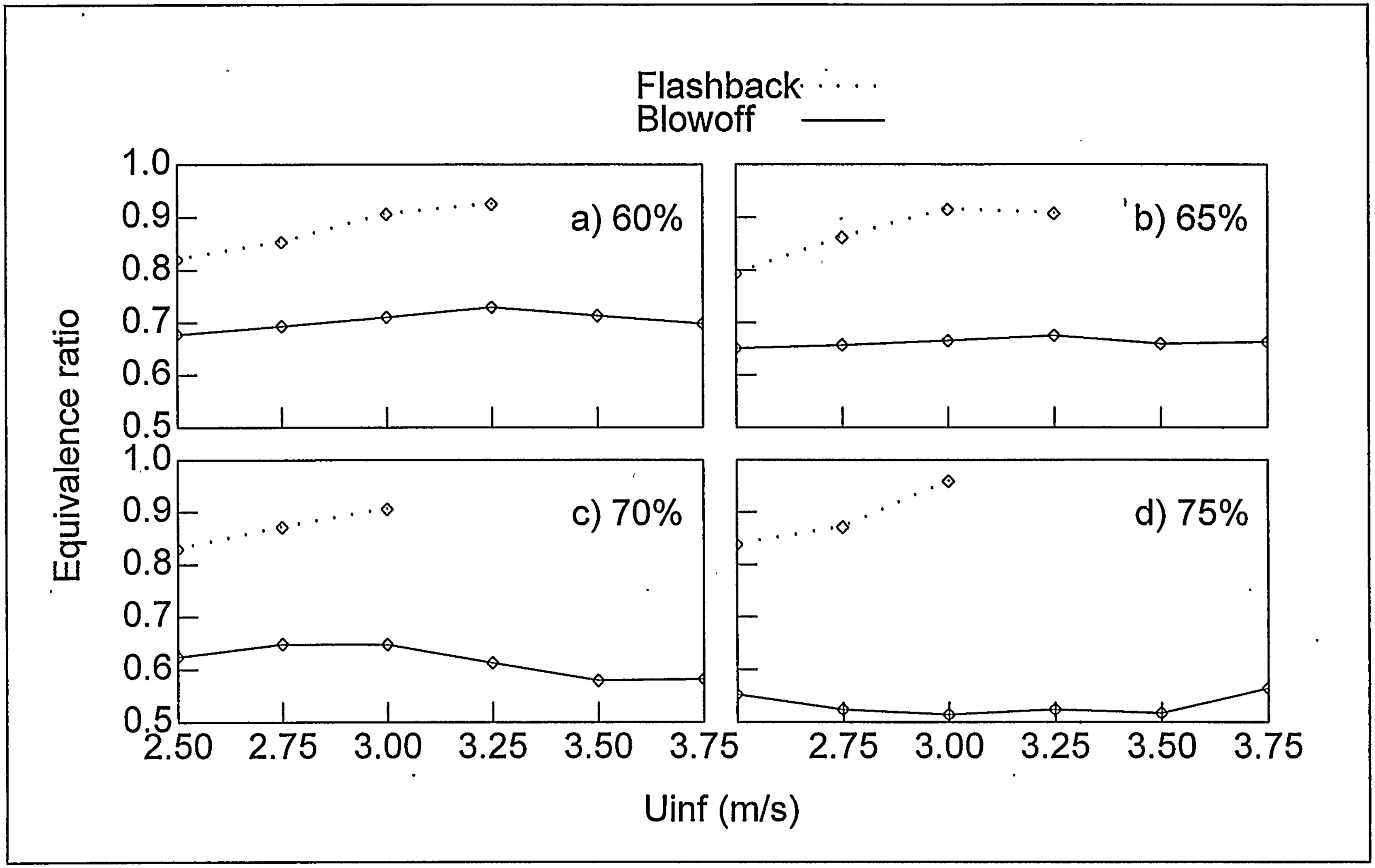

Figure 6: Operating range for vane swirler; increasing blockage gives broader operating range due to lower blowoff limits.

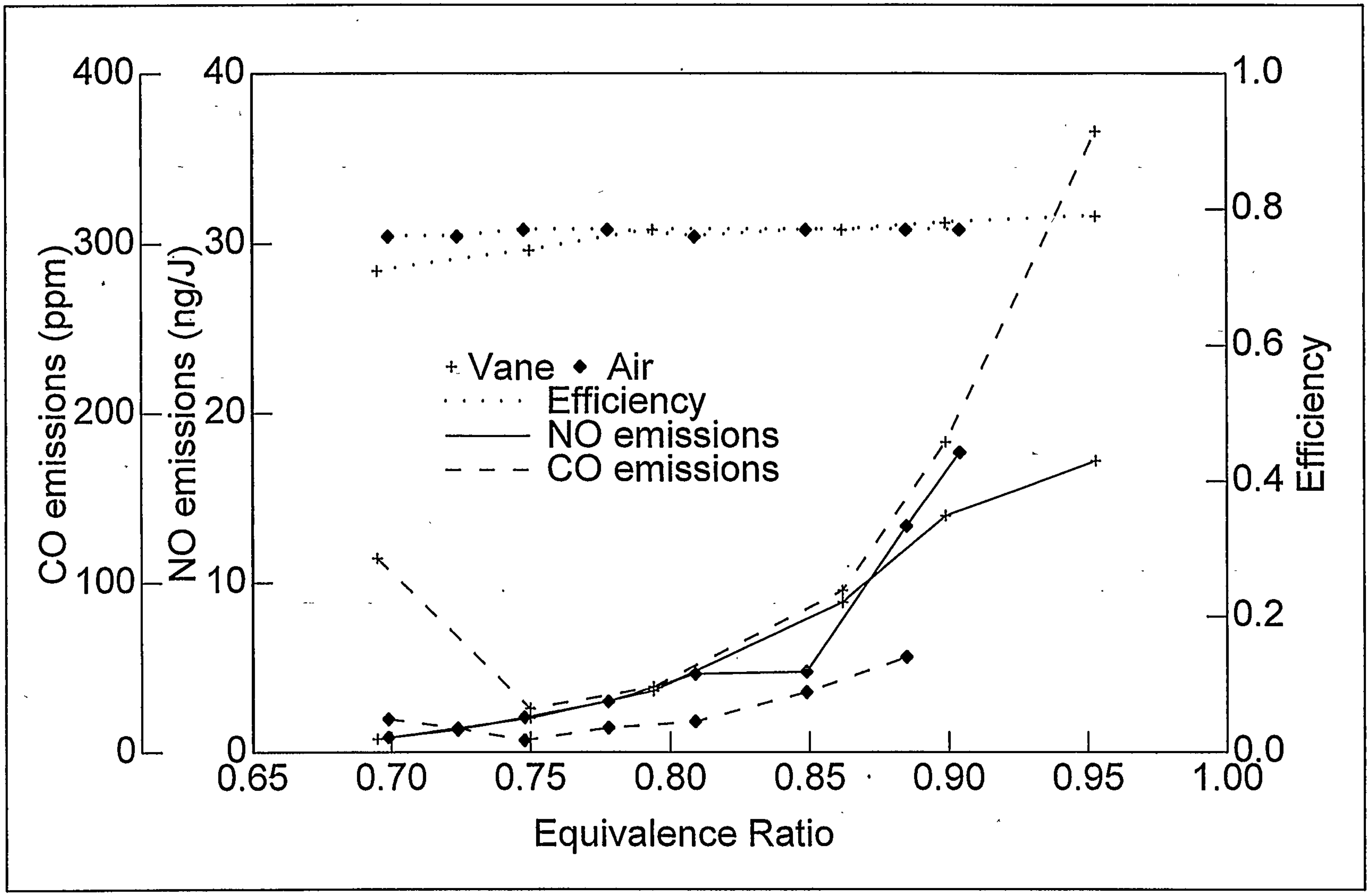

Figure 7: Emission/thermal efficiency comparison for an air-swirled and a vane-swirled WSB operating in a Telstar heat exchanger.