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BREAK UP OF VORTEX RINGS IN IMPINGING TURBULENT JET FLAMES.(U)
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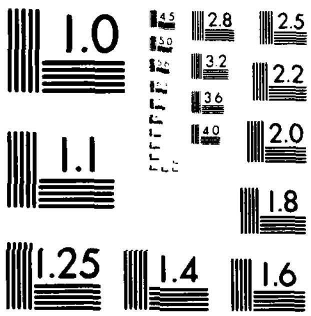

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The objective of this experimental investigation is to examine the structure of turbulent flow in jet flames inpinging on flat walls with particular emphasis on the formation and break up of vortex ring-like eddies. Experiments include the study of heat transfer to the wall, and the influence of eddies on the mechanism of heat transfer, with variation in flow geometry and burner initial conditions. During the first year of research a new flame-impingement rig has been commissioned, preliminary flow visualisations have

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been made showing flame structure over a wide range of conditions. Considerable data have been obtained in non-impinging flames, which will later be compared with impinging flame data. As a result of this preliminary work it is found that ring vortex eddies are identified in impinging flames for a wide range of flow geometries, equivalence ratios and types of gaseous fuel. These eddies break up into 'flamelets' which remain coherent for long distances. These coherent structures require further investigation because they must strongly influence heat transfer to the wall and fluctuations in gas temperature near the wall. Similar structures have been identified and measured in non-impinging flames.

BREAK UP OF VORTEX RINGS IN IMPINGING TURBULENT JET FLAMES

Annual Technical Report

by

A. J. Yule and N. A. Chigier

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Abstract

The objective of this experimental investigation is to examine the structure of turbulent flow in jet flames impinging on flat walls with particular emphasis on the formation and break up of vortex ring-like eddies. Experiments include the study of heat transfer to the wall, and the influence of eddies on the mechanism of heat transfer, with variation in flow geometry and burner initial conditions. During the first year of research a new flame-impingement rig has been commissioned, preliminary flow visualisations have been made showing flame structure over a wide range of conditions. Considerable data have been obtained in non-impinging flames, which will later be compared with impinging flame data. As a result of this preliminary work it is found that ring vortex eddies are identified in impinging flames for a wide range of flow geometries, equivalence ratios and types of gaseous fuel. These eddies break up into 'flamelets' which remain coherent for long distances. These coherent structures require further investigation because they must strongly influence heat transfer to the wall and fluctuations in gas temperature near the wall. Similar structures have been identified and measured in non-impinging flames.

CONTENTS

Introduction

In many practical combustion systems jets of high velocity reacting flow impinge on the internal walls of a combustor. For the U.S. Army, an important example of the occurrence of this phenomenon is within the cylinders of internal combustion engines. However impinging flames can also occur within turbojet engine combustors, at the exhausts of turbojet engines and in many larger systems such as furnaces. When a flame impinges on a wall, the principal phenomenon of interest is the heat transfer to the wall. Both the time averaged and the local instantaneous heat transfer are important. In the case of a cylinder wall, the peak temperature and velocity of the gas near the wall is of importance in determining the required properties of the wall material, particularly for the case of new designs of 'adiabatic' engine. This is one reason why the fluctuating, and thus turbulent, structure of an impinging flame is of importance. However the turbulence is also the principal mechanism of transport of hot gas to the wall and also controls the mixing and reaction of the fuel in diffusion flames and the reaction zone structure in premixed flames. Thus both the time averaged and fluctuating rates of heat transport are controlled by the turbulence structure and by a complex interaction between this structure, reaction and the wall itself. As a further motivation for studying the turbulence structure of impinging flames, the wall is known to affect the mixing rates and combustion efficiency of the impinging flame and also affects pollutant formation by, for example, quenching and thus promoting soot formation.

As a result of early work[1] at Sheffield University on very large impinging flames, relevant to furnaces, it was noted that very clear coherent eddies could be seen in these flames. These large eddies were identified by pockets of flame, or 'flamelets', which often remained identifiably coherent for the complete distance from the centre to the edge of the round plate. In recent years the 'turbulence community' has come to recognise[2] that coherent structures form an essential feature of many turbulent flows and these structures must be measured and understood if advances are to be made in modelling techniques. Coherent structures are large, strong eddies which retain their coherence for long downstream distances. It would appear that a flame impinging normal to a flat plate, provides a very clear visualisation of such eddies. Thus this investigation of turbulence structure in impinging flames, includes emphasis on the roles of these eddies, and their wall interactions, in determining heat transfer and reaction rates. Cine films show that these eddies can be formed from the breakdown of vortex rings nearer to the point of impaction, or even in the jet before it impacts on the wall; hence the title of this investigation.

The evidence so far indicates that the eddies are a 'fluid mechanical' phenomenon which is modified, and clearly visualised by reaction, but is not itself a result of combustion. Thus this research is carried out in parallel with a cold flow experiment (also U.S. Army supported) in which sophisticated hot wire data analysis techniques are used to investigate the turbulence structure of impinging turbulent cold jets. This latter work is carried out under the direction of Professor Mathieu at L'Ecole Centrale, Lyon, France.

Qualitative Description of Impinging Flame Structure

Figure 1 shows the notation for the present investigation of flames impinging on a flat plate. The geometry is axisymmetric to aid data interpretation in terms of flow structure. In all cases to be studied, the fuel gas impacts vertically on the plate from below. This is to ensure that the flow is not unstably stratified. For the case of a flame impinging vertically downwards on a plate, the hot gas, near the plate, is unstably stratified so that buoyancy induced instabilities could result at low velocities.

As a preliminary stage in this investigation, and to aid the design of the main rig, parameters in a set of impinging flame arrangements were varied over a wide range. Simple arrangements of flames from cylindrical tubes, with thin steel plates were used in addition to a water cooled plate and also a plate covered with heat insulating material. The impinging flame structure was studied using high speed cine photography, still photography and direct visualisation by eye, for a wide range of parameters. Geometric parameters were varied in the ranges (see Fig. 1): $0.25\text{m} < D < 2\text{m}$, $2\text{mm} < d < 15\text{mm}$ and $5\text{mm} < \ell < 250\text{mm}$. In addition the properties of the fuel gas leaving the nozzle were varied by using: (i) propane, (ii) natural gas, (iii) propane premixed with air and (iv) propane diluted with nitrogen.

In all of these cases the appearances of the flames are similar in character to those sketched in Figure 2. Figure 2 shows how, for a fixed geometry, gradually increasing the fuel flow rate causes the observed structure of the flame to pass through a series of distinct stages. In all of these stages the flow structure is visualised by the light and dark regions, corresponding roughly to the occurrence and non-occurrence of significant local reaction. The reaction zones (or 'flamelets') and the turbulence structure are intimately linked; so that coherence and orderliness in visible reaction zones must also be indicative of the coherence and orderliness of eddies.

As shown by Figure 2, at low flow rates reaction occurs in axisymmetric 'flamelets' which grow in diameter until they reach the edge of the plate. Extinction of these ring flamelets may occur before they reach the plate edge and then, for the case of diffusion flames, the rings may then be marked by concentrations of soot. As indicated in Figure 2 (b), an increase in gas flow rate causes the ring flamelets to undergo a three-dimensional breakdown as they grow and move from the impingement zone. Azimuthal waves grow and a 'pinching' of the rings occurs.

As indicated by Figure 2 (c), at still higher flow rates, the reaction zones break up into individual 'flamelets'. These tend to have a length, in the radial direction, on average three times their width. Near the impingement zone, these flamelets retain an orderly azimuthal arrangement, so that 'rings' of flame can be seen by eye. However this azimuthal coherence reduces as the flamelets move outwards, until they appear to be randomly distributed.

As the flow rate is increased further (Fig. 2 (d)), the same general flow exists although the flamelets tend to reduce in size.

All of these various types of flow can be identified for variation in fuel flow rate, for all of the geometries and fuel gas compositions used. As would be expected, premixing or diluting with nitrogen produces less luminous flames, and may produce changes in eddy sizes and passing frequencies. However the basic pattern of coherent eddies can always be identified. Cold flow experiments, at Stanford University, have shown that similar structures can be identified in impinging submerged water jets. Thus these coherent structures are 'fluid dynamic' phenomena which may be modified by combustion, but which are not created by reaction effects.

Figure 3 indicates how variation in fuel gas composition, flow rate and geometry, can change the region of flame stabilisation. Thus at low flow rates (Fig. 3 (a)) a steady laminar flame impacts on the plate and instabilities grow in the reacting wall jet on the plate. Figure 3 (b) shows the situation in which eddies can be seen in the free jet flame before it impacts on the plate. It seems likely, but is not yet proven conclusively, that the free jet eddies persist during impaction, to form the eddies in the wall jet flame. Under certain conditions of flow rate, composition and geometry, flame stabilization can occur in the impaction zone. For this situation (Fig. 3 (c)) there appears to be a strong pulsation in the flame in this zone. This oscillation forms the eddies seen further out on the plate and it is likely that there is a feedback mechanism from the reacting flow in the impaction zone to the gas jet, which controls the initial frequency of production of eddies. Cold, impacting air jet experiments at UCLA indicate that a strong acoustic feedback mechanism can occur.

As indicated by Figure 3 (d), at high jet velocities flame stabilization can occur in the turbulent wall jet on the plate. However the coherent flamelets are still seen in this situation.

Figures 4 and 5 show models of the coherent flamelet eddies which have been seen in the flow visualisations. One purpose of the measurement program is to verify these models and quantify the roles of these eddies in the mixing, reaction and heat transfer processes. Figure 4 indicates a cross-section of the flamelets seen in the cases shown in Figures 2 (a), (b) and (c). The flow is essentially 'transitional' in that the boundary layer is laminar. As indicated in Figure 5, at high velocities one must expect to have turbulence generated near the wall, in addition to the jet-like turbulence in the outer layer. In both cases reaction occurs predominantly at the outer edges of the large eddies, where stoichiometric conditions are found.

In spite of the regularity of the observed flows, the fluid mechanics of impinging turbulent jets are complex. Figure 6 indicates some of the phenomena experienced by vortex rings, in a jet, as they impact on the plate. Phenomena observed in the impinging flames have basic similarities to those observed in round free jets[3] and jet flames.[4] In free jets transitional vortex rings near the nozzle break down via azimuthal waves, into three-dimensional turbulent large eddies. Thus the ring flamelets in the impinging flame (Fig. 2(a)) are vortex rings. The flamelets in the impinging flame also coalesce, as observed in free jets.

Experiment for Measurement of Impinging Flame Structure

Based on the preliminary observations noted above, an impinging flame rig has been constructed which is large enough to make detailed flow measurements within the flame, but which is smaller than has been used in the past, to more closely model practical combustion systems. The flame impacts on a 415mm diameter steel plate. The plate can be used with and without a ceramic insulating layer. The wall temperature can be measured by an array of Chromel-Alumel thermocouples. Screw-in burner nozzles with diameters between 1mm and 10mm can be used. The height ℓ can be varied between 0 and 300mm. A micromanipulator is used to position probes within the flame. The complete impinging flame rig is transportable so that it can be positioned above an existing laser anemometer rig, for measurement of gas velocity.

The experimental plan is divided into two phases. Firstly an 'overall' investigation in which wall and gas temperatures, and velocity fields will be measured with systematic variation in the flow parameters. Cine films will be taken and analysed of the different flows. This provides a data base which is currently lacking for the impinging flame situation. The second stage involves a very detailed investigation of the turbulence structure for one of the impinging flame cases. The investigation concentrates on the roles of the coherent flamelets. Use is made of high temporal and spatial resolution measurement techniques which have been developed in free jet flame studies (see below). Conditional sampling techniques are used to measure the velocity and temperature fields of the flamelets. Ionization probes are used to identify reaction zones. The results of the free jet flame study are reported below.

Structure of Free Jet Flame

The investigation of the free jet flame has the same basic approach as the impinging flame investigation. Thus measurements have been made of flow characteristics for a wide range of initial fuel jet velocities and equivalence ratios. In addition very detailed measurements have been made of flow structure for a small number of selected flames at certain positions. The results to date have been reported in two recent papers[4, 5] and only a brief outline of the observations relevant to the impinging flame investigation will be given. It has been shown that jet flames develop into turbulence from initially laminar conditions via a region of vortex ring eddies. These vortex rings break down via azimuthal waves and eventually large eddies are formed. This process is similar to that found in cold jets and can be identified in jet flames in both direct visualisations and high speed schlieren films. This flow deforms the reaction zones in the flame so that the vortex rings and eddies are delineated by regions of reacting flow. Ionization probes have been developed to detect these zones and, for example, Figure 7 shows frequency spectra in the mixing layer of the jet flame at different heights x above the burner nozzle (diameter D). The peaked spectra near the nozzle result from the periodic vortex rings. Typically turbulent spectra are found further downstream. Thus the spectra can be used to determine the transition length of the jet flame. For the case $Re = 10^4$ and equivalence ratio (propane/air) = 10.4, the transition distance is $x = 12$ D compared with $x = 5$ D for the cold flow with the same Reynolds number. The jet potential core increases more than the transition distance, between the cold and burning cases. For example laser anemometer measurements of velocity (Figs. 8 and 9) show that the potential core length increases from $x = 4$ D to $x = 24$ D between the cold jet and jet flame cases. These results show the strong influence of combustion on the transitional flow in a jet and this has repercussions when interpreting the results in the impinging flame experiment: vortex ring structures can be expected to persist much longer in the flame case and it is important to ensure that transitional flow structures in the impinging flame are not wrongly interpreted as turbulent eddies.

Discussion and Concluding Remarks

The first year of this project has been one of preliminary experimentation and rig construction. However there has been confirmation, from the many flames studied qualitatively, that coherent large eddies are an important feature of all impinging flames. The vortex ring eddies, and the three-dimensional 'flamelets', appear to be directly comparable with the similar structures observed in transitional and turbulent flow in free jet flames. Thus the coherent structures in the impinging flames are jet-type phenomena, rather than originating from wall or combustion effects. It seems most likely that certain peculiarities of the impinging flame flow make the coherent eddies more clearly visible in this flow, than in round free jet flames, although the actual structures and behaviours of these eddies are basically similar. For example the outward flow of eddies, from the impingement zone, tends to keep the eddies separated and, in the impinging flame, one does not have the confusion between the two sides of the flow, which is unavoidable in free jet flame visualisations. From the practical point of view, understanding and modelling the turbulence structure of impinging flames is of importance. The clearly observed coherent large eddies make this flow an ideal case for the application of new multiprobe conditional sampling techniques to measure individual eddy structures and their roles in mixing, reaction and heat transfer. Agreement is growing that these eddies are the 'building blocks' of turbulence and they must be included in future, more reliable, models of turbulent reacting, and non-reacting, shear flow.

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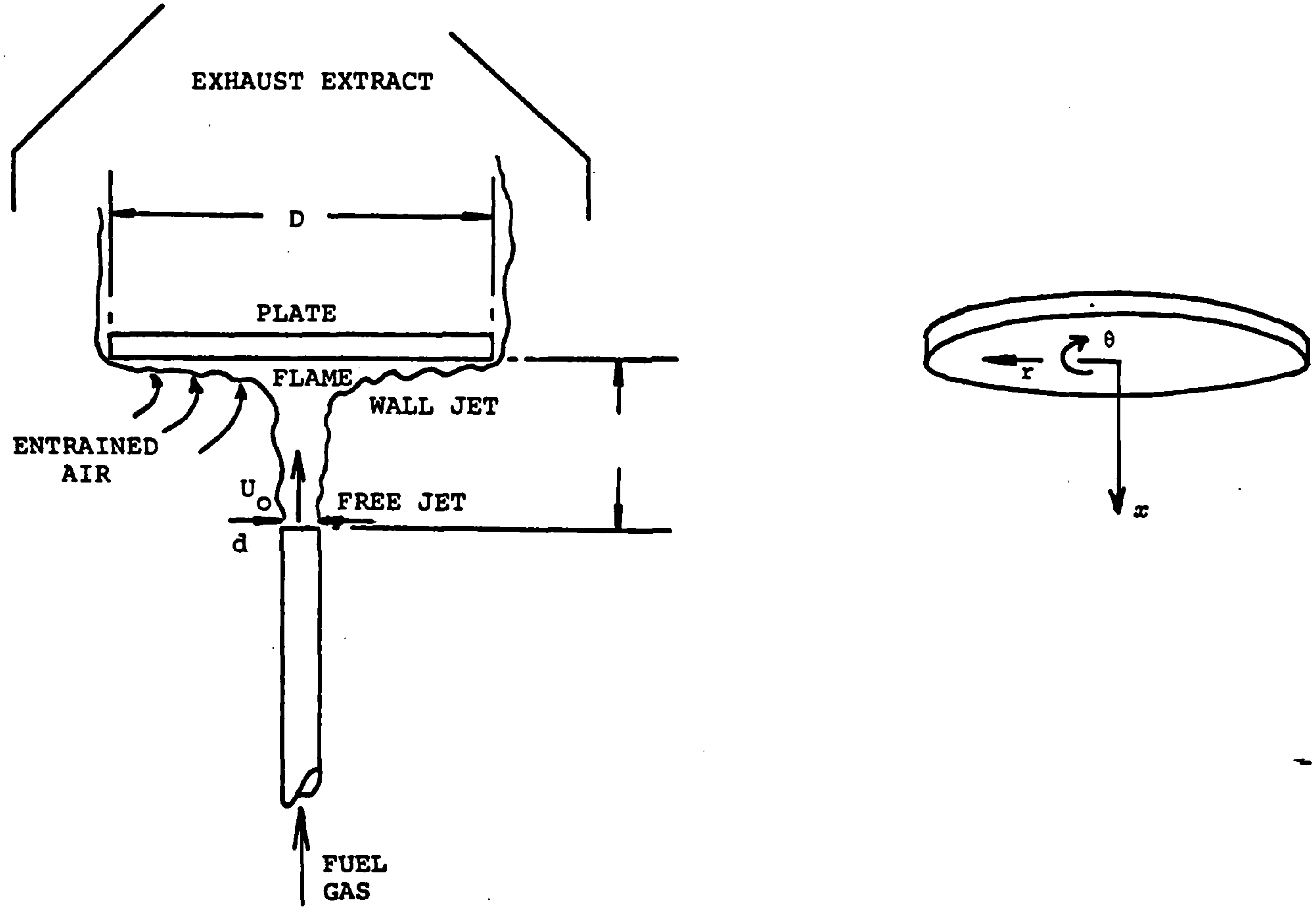


FIGURE 1. Notation for vertical jet flame impinging on a round flat plate

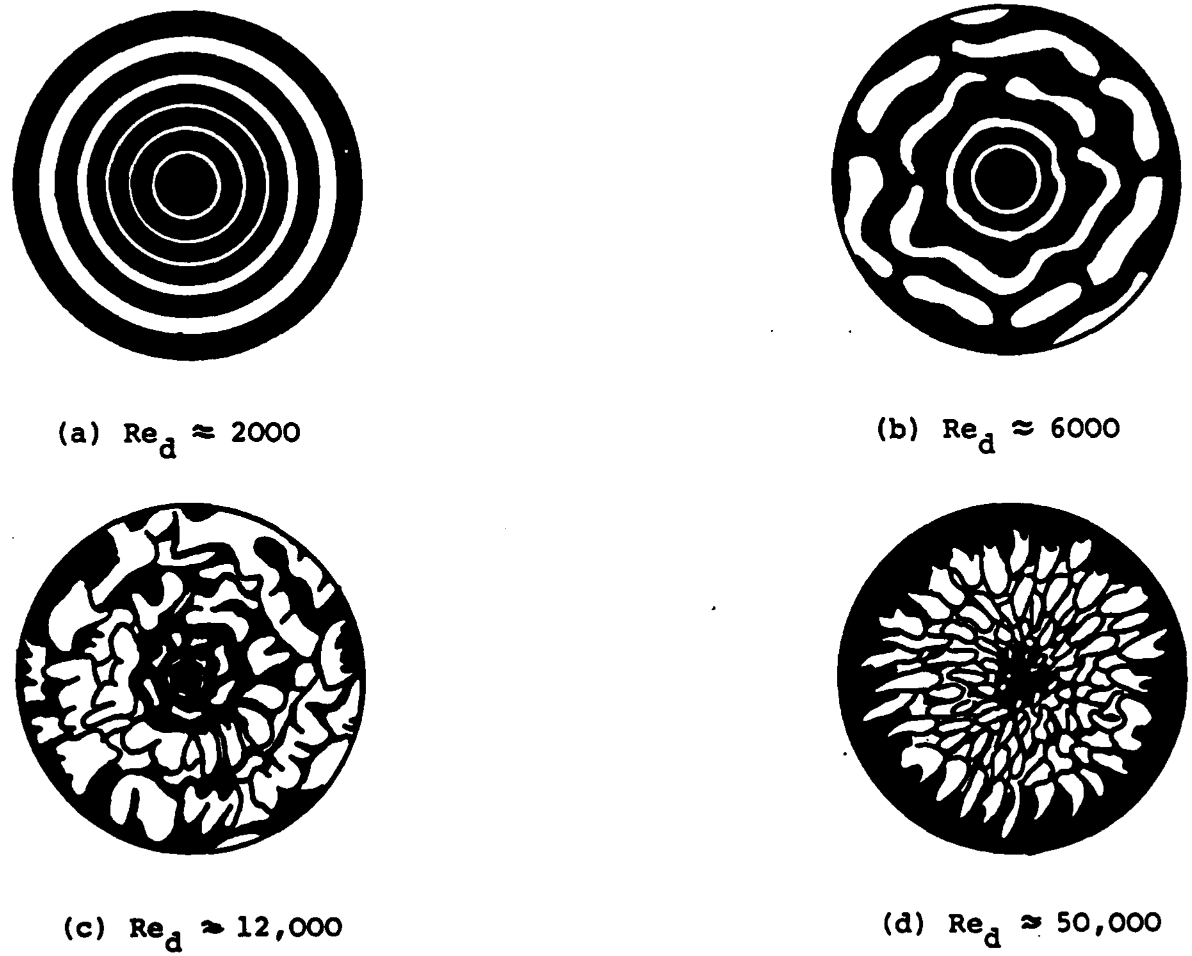
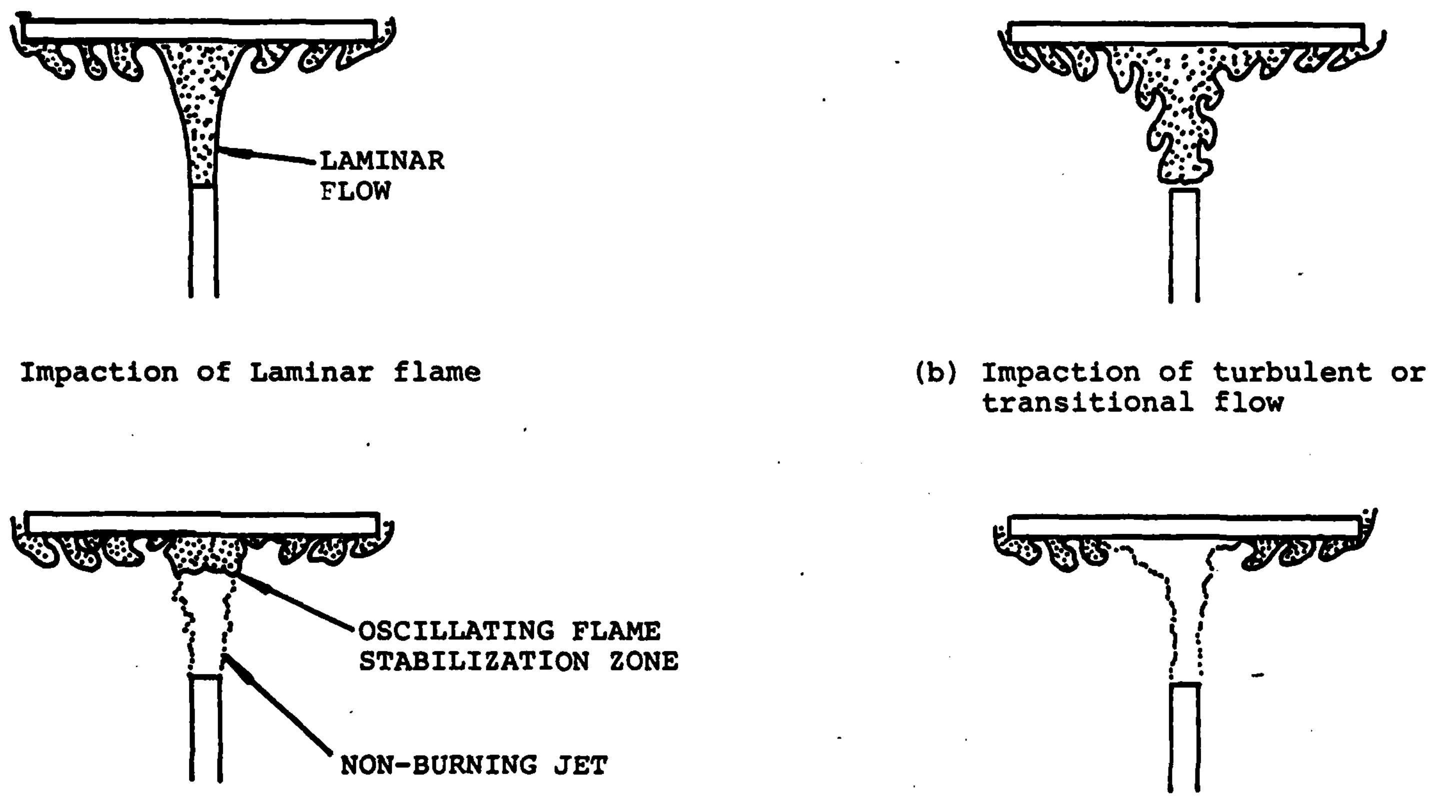


FIGURE 2. Instantaneous visual appearance of impinging diffusion flame at different Re, d = 10mm
Light regions indicate luminous reaction zones



(a) Impaction of Laminar flame

(b) Impaction of turbulent or transitional flow

(c) Stabilization at impaction zone

(d) Stabilization in wall jet

FIGURE 3. Observed modes of flame stabilization

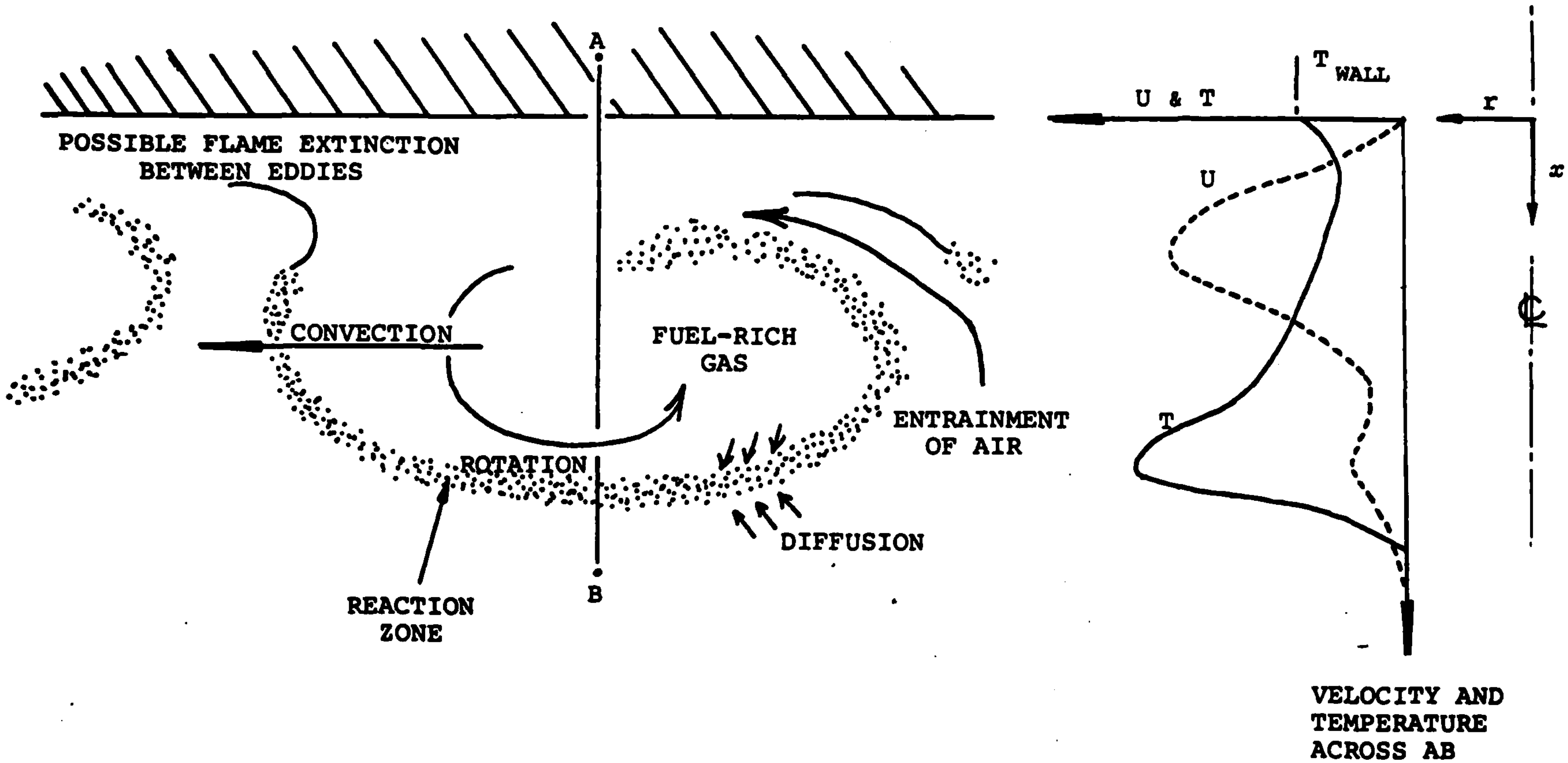


FIGURE 4. Cross-section of eddy in wall jet of impinging flame at moderate Re

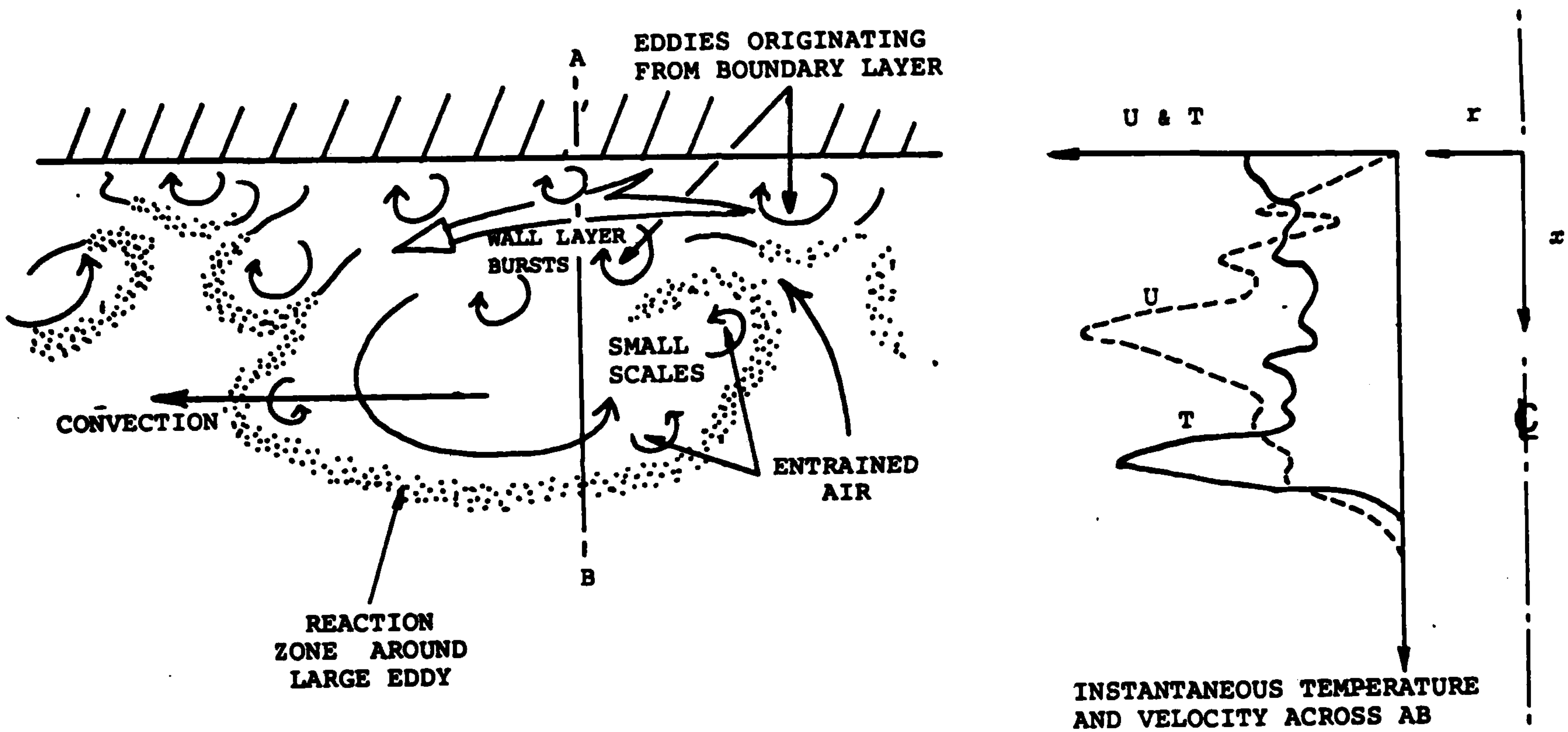


FIGURE 5. Model of flamelet in impinging flame at high Re

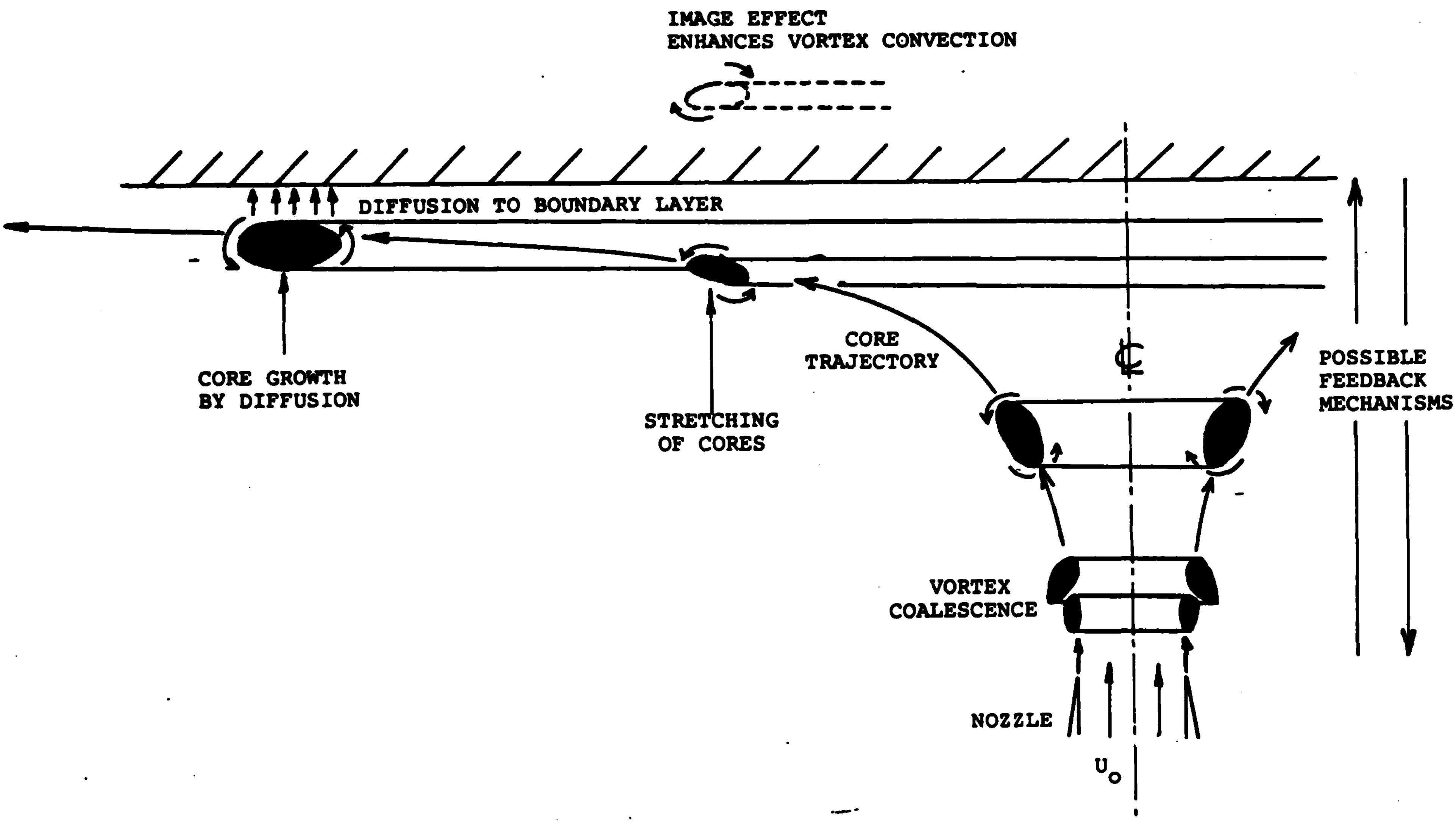


FIGURE 6. Impaction of vortices on wall

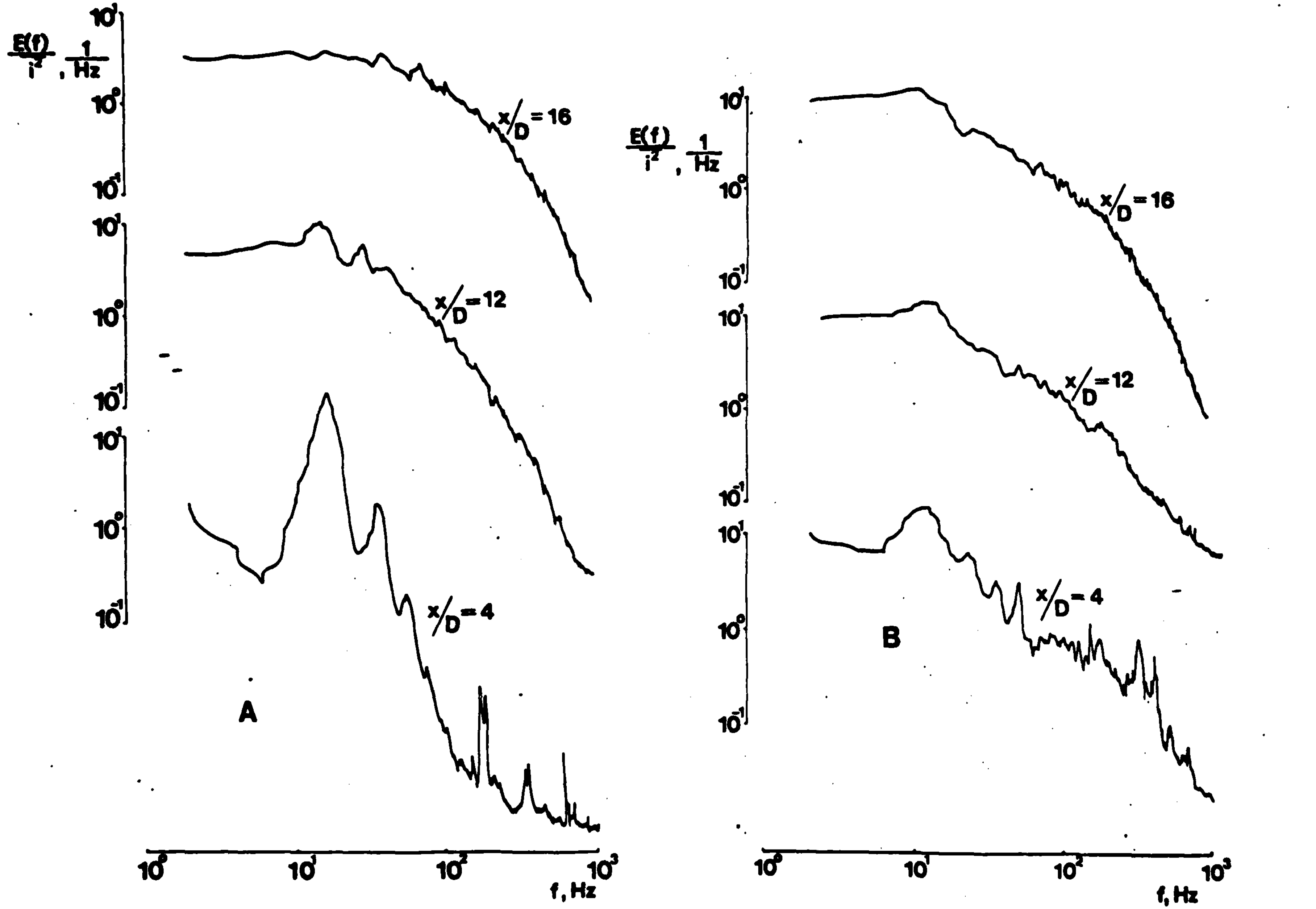


FIGURE 7. Power spectra of ion current at different longitudinal positions in two flames: Re = 10^4, r/D = 0.5, equivalence ratios: (A) ϕ = 2.62; (B) ϕ = 10.4.

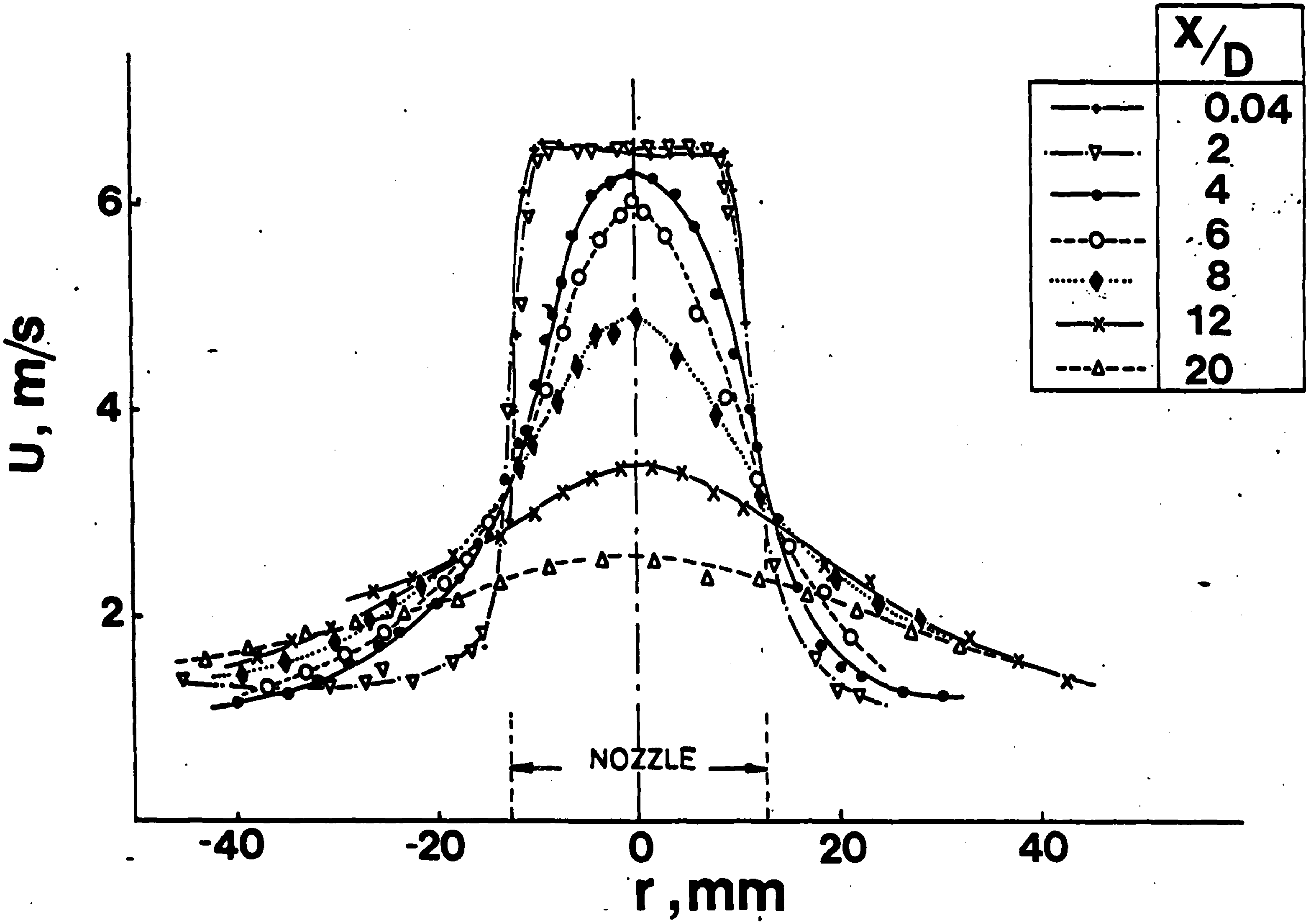


FIGURE 8. Mean velocity profiles in jet with Re = 10^4.

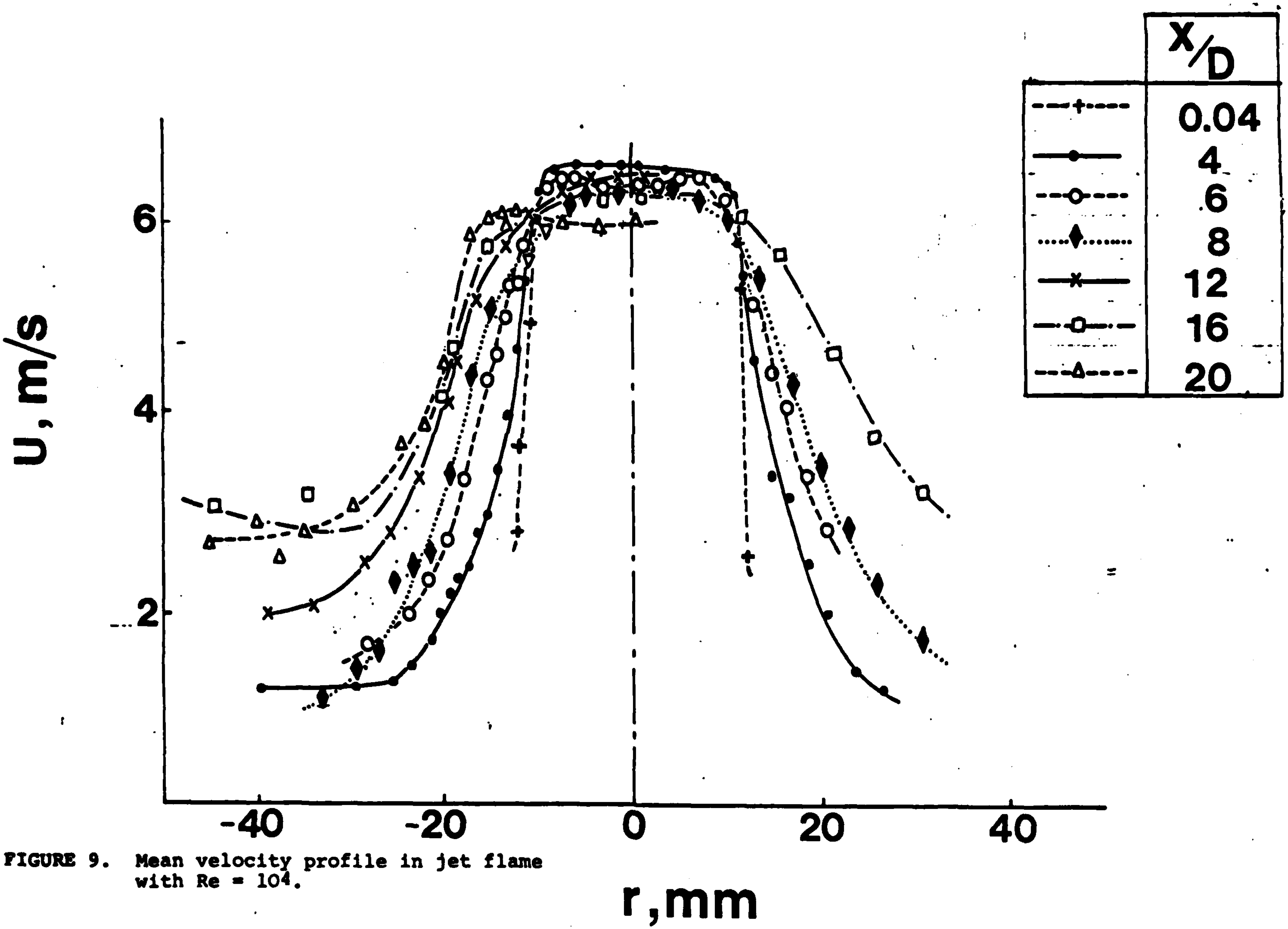


FIGURE 9. Mean velocity profile in jet flame with Re = 10^4.