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The flow field in turbulent round free jets

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ABSTRACT

A critical review of both experimental and computational studies of round turbulent jets is provided, beginning with the work of Tollmien (1926). This review traces the history, the major advances, and the various stages that the research community went through over the past 85-odd years—from statistical analyses through to the use of conditional sampling, proper orthogonal decomposition and structural eduction methods. It includes the introduction of novel experimental techniques as well as insights gained from recent large eddy and direct numerical simulations. Some direction where future research may prove beneficial is also provided.

The review does not include the effects of passive or active control, scalar contaminant transport whether by heat or mass. It includes effects of Reynolds number, inlet conditions (excluding swirl) and considers both near- and far-field investigations. We have minimised reference to papers that utilise models of turbulence unless such works provide something of particular importance.

Contents

1. Introduction

The study of turbulent flow has evolved over the last century from a curiosity to an intensely explored research theme. During this period, the physical insight that we have gained has developed alongside the evolution of theoretical, experimental, and computational methods. In the broadest view, progression in turbulence research may be seen as periodic. Numerous research groups around the world have emerged as 'schools' in turbulence during developmental periods built upon then-current ideas; these schools were built around statistical, experimental, computational, and other methods.

Here is a **very** brief description of idealogical paradigms and the inception of their associated schools. The basic ideas of Reynolds and Prandtl gave rise to a school of statistical turbulence that laid the

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groundwork for computational turbulence and its schools on both modelling and simulation. Experimental turbulence research began with simple Pitot tubes, followed by hot-wire anemometry and today's advanced laser-based methods that are fast approaching the fidelity in space and time that is currently solely the purview of direct numerical and large eddy simulation (DNS, LES). From the application of these techniques and technologies the bewildering array of length and time scales, embodied as we now know within turbulence and its structure, has emerged to challenge the turbulence community to control turbulence rather than to merely design and build devices that are subject to the 'whims' of a flow.

Canonical turbulent flows include boundary layers, channel flows, the wake, jets, and others. Each of these has an extensive literature which appears to grow ever more as we direct ever improving tools and techniques toward, according to Richard Feynman 'the last great unsolved problem in classical physics.' In this paper, we review the 'simple' free round turbulent jet that carries no additional thermo-physico-chemical effects (such as density variation, heat release, et cetera) and that operates in the absence of any geometric modifications to the nozzle (such as lobes, for example). Nozzle effects are considered only insofar as their use to illuminate flow physics and improve our understanding of flows.

2. The round jet: from birth to death

The jet is borne out of the nozzle exit plane. As the jet issues into a quiescent environment, as supposed here for this review, it will eventually entrain the receiving fluid and spread in the radial direction with downstream distance until the initial momentum is spread very thinly to the point where viscous action will dissipate energy and lead to the 'death' of the jet.

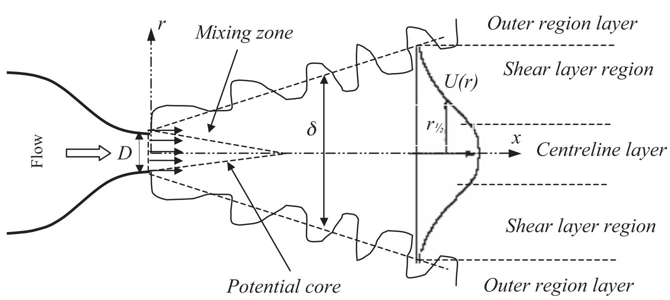

Fig. 1. Schematic of a free jet issuing from a smooth-contraction nozzle and its co-ordinate system.

Even though downstream development of jets depends on both initial and boundary conditions, it is possible to define a generic co-ordinate system that can be applied to the majority of jet flows. The flow field geometry of a jet issuing from a smooth nozzle is shown in Fig. 1. A polar co-ordinate system is used, as shown, with the x-direction aligned with the nozzle axis. The velocity components in the x, r, and θ co-ordinate directions are denoted U, V, and W, respectively. The terms in the Reynolds decomposition are herein denoted $u=U+u'$, $v=V+v'$, and $w=W+w'$. From the nozzle with outlet diameter D flows a Newtonian fluid with characteristic velocity U_j. The centreline velocity is U_c. A commonly used characteristic length, the jet half-radius $r_{1/2}$ is determined by $U_{r_{1/2}}=U_c/2$. The local time-averaged diameter of the jet is denoted δ and is referred to as the outer scale. All data gathered from the literature are herein referred to in this manner.

In Fig. 1, the convoluted edge represents the shear layer between the high vorticity jet flow and the nearly-at-rest surrounding fluid [1]. As air from the irrotational ambient fluid is entrained, the mass flux of the jet increases with axial position x; momentum flux, however, remains, as it must, constant.

Different axial regions are defined in the axisymmetric round jet: the near field, the intermediate field, and the far field. The near field, defined by its potential core which appears only for jets issuing from a contraction nozzle, is a region of flow establishment; its flow features meet those of the surrounding mixing zone and cause the development of turbulence; it is usually within $0 \leq x/D \leq 7$.

The initial instability modes, created by the jet at its source, produce the flow structures in the shear layer (or mixing zone); the resultant vortices will roll-up and then pair-up, as depicted in Fig. 2. The intensity of vortex pairing depends on initial conditions (being much weaker or non-existent in pipe jets, for example). The mean velocity profile at the exit is determined by its geometry; a nozzle, pipe, or sharp-edged orifice will each produce a top-hat, power-law-type, or complex converging-diverging flow profile, respectively. Historically, as is discussed later, the flow characteristics created by these profiles were believed to be washed away as the flow evolves downstream into the far field;

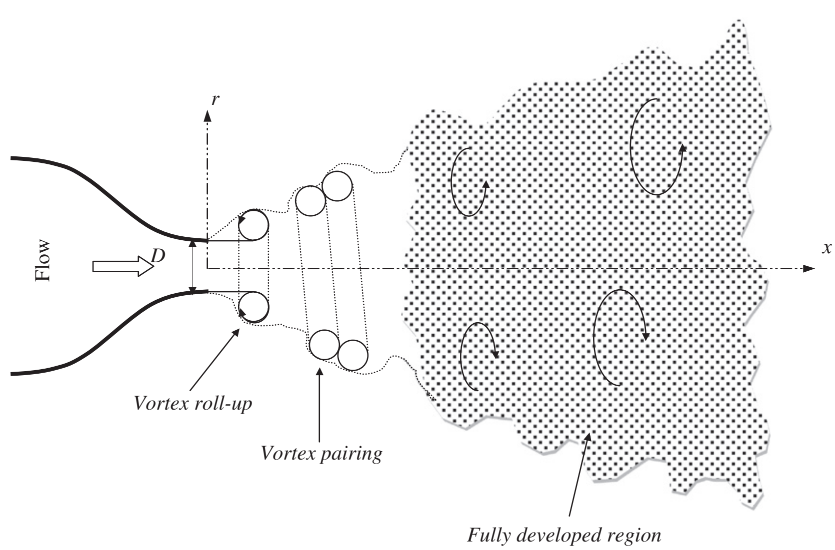

Fig. 2. Flow features of the free round jet.