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On the flow field generated by a gradually varying flow through an orifice

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ABSTRACT

The motion of a vortex ring generated by gradually varied flows through a thin-edged orifice has been investigated experimentally using particle image velocimetry. This flow reproduces the primary characteristics of many biological flows, such as cardiac flows through valves or jellyfish and squid propulsion. Even though vortex ring formation has been extensively studied, there is still interest in gradually varying inflows, i.e. the ones that are mostly found in previous conditions. The main purpose of this paper is to extend the time scaling already proposed in the literature to the entire cycle of vortex ring formation, pinch-off and free motion. To this end, eight inflow time laws have been tested, with different acceleration and deceleration phases. They have been selected in relation to practical applications by their resemblance to the main characteristics of cardiovascular and pulsed locomotion flows. Analysis of measured velocity and vorticity fields suggested a general criterion to establish the instant of vortex pinch-off directly from the imposed velocity program. This allows the proper scaling of the entire time evolution of the vortex ring for all tested inflows. Since it is quite easy to identify this instant experimentally, these results give a simple, practical rule for the computation of scales in vortex ring formation and development in the case of gradual inflows. The "slug model" has been used to test the proposed scaling and to obtain predictions for the vortex position, circulation and vorticity which are in agreement with experimental data.

1. Introduction

The sudden onset of a jet in a fluid at rest generates a vortex ring that begins to travel in the direction of the jet axis. Typically, the vortex ring grows up to a limiting value and, if the flow continues further, it detaches from the trailing jet which no longer contributes to the increase of its circulation but rather produces a vorticity layer in its wake. Understanding this type of phenomenon is of fundamental importance for a wide range of applications, such as intraventricular flows and the propulsion of aquatic animals. The link between the characteristics of the jet flow and the features of the resulting vortex ring has been investigated extensively in the past [1,2]. Theoretical analysis and modelling, such as those of Tung and Ting [3] and Saffman [4], predicting the travel velocity of a viscous vortex ring, and the study by Pullin [5], using similarity theory to predict the main parameters of vortex rings originated both by tubes and orifices have been also carried out. On the basis of experimental observations [6], Mohseni and Gharib [7] suggested an analytical model predicting a parameter limiting their growth, i.e. a limiting value for the circulation around the vortex ring. Kaplanski and Rudi [8] proposed a model that also accounted for the viscosity, while Krueger [9] included the pressure field by showing that this correction is important only in the presence of sudden temporal variations. Experimental investigations were initially based on visualisations [10,11], revealing that the details of the forcing used to push the flow through the orifice are important. With the advent of digital imaging, many investigators began to use particle image velocimetry (PIV) to measure velocity and vorticity fields [12–15]. In particular, Gharib et al. [6] determined the time of pinch-off and introduced the idea of a limiting non-dimensional time in the development of the vortex rings. Krueger and Gharib [16] used PIV and hot film anemometry to explore the relation between the velocity field originated by a starting jet and the resulting thrust.

Though it is well known that this phenomenon is affected by the so-called velocity program, i.e. the variation of the flow rate with time, most investigators have focused their work on the development of vortex rings using very simple laws of motion: namely, constant flow rate ("impulsive program"), flow rate increasing in a linear way over time, or a combination of them in a "trapezoidal program". Glezer [10] reported results from different velocity programs and proposed a factor that should account for all the variations of the flow rate in time. In particular,

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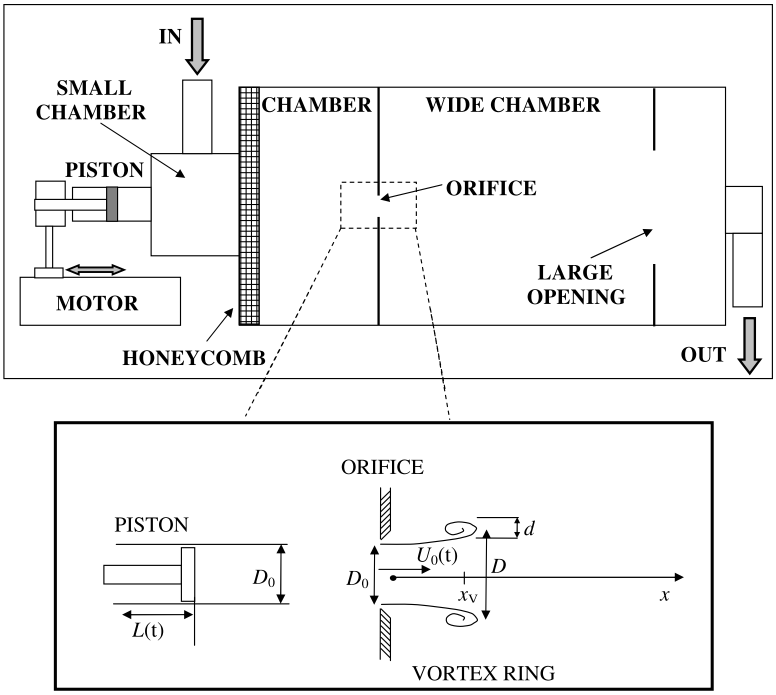

Fig. 1. Experimental set-up. Details of the orifice and piston are given in the inset.

this velocity program factor (defined as the normalised mean square value of the forcing signal) allowed for the proper scaling of vortex circulation for a wide range of velocity programs. Rosenfeld et al. [17], in a numerical simulation, noticed that pinch-off can be meaningfully delayed by using a constantly increasing flow rate. Krueger and Gharib [16] observed experimentally that negative-slope velocity programs determine earlier non-dimensional pinch-off times than positive-slope ones. Recently, Shusser et al. [18] discussed the effect of the time variation of the exit flow rate in terms of impulsive, linear and trapezoidal velocity programs.

Despite the fact that such schematic programs are conceptually easier to deal with, in nature there are cases in which the flow rate increases gradually over time and then decreases again, without any abrupt change in the slope of the curve, leading to very high (indeed, potentially infinite) peaks in acceleration [19,20]. For instance, this characteristic is typical of biological flows – such as in jellyfish [21] and squid [22] locomotion – and cardiovascular flows, such as the intraventricular flow through the mitral valve [23,24]. In such flows, the exit velocity is characterised by non-monotonic variations over time, which are expected to affect the formation of the vortex ring in a non-trivial way. In any case, there is no unequivocal event that triggers the end of that process, such as a sudden stop of the flow rate or a sharp change in the slope of the velocity program. In a recent paper, Danaila and Helie [25], following Maxworthy [26], tested the time scaling of vortex velocity and circulation at intermediate Reynolds numbers. They considered the whole process of vortex formation, pinch-off and free motion. However, it is important to note that, in this case as well, the velocity program driving the flow was impulsive with short acceleration and deceleration phases.

The purpose of this study is to reproduce the salient characteristics of biological flows in a laboratory in order to expand knowledge about vortex ring behaviours. To this end, the flow generated by gradually varying velocity programs downstream of a thin-edge orifice was investigated in the laboratory using PIV. The main question we are going to address is whether there is any simple rule which permits the reliable estimation of the scales describing all the phases of the phenomenon, including inflow acceleration and deceleration, for a large set of forcing signals. To answer this question, the velocity and vorticity fields resulting from different gradually varied velocity programs with different acceleration and deceleration behaviours have been examined. A criterion for determination of pinch-off and proper time scaling of the phenomenon is proposed by considering the instant when the inflow through the orifice does not influence the behaviour of the vortex ring anymore. The observed results are compared with predictions obtained using the so-called "slug model" [10,2]. In the next section, we will briefly describe the methods and equipment we used, whereas in Section 3 we will present the flow behaviour, model predictions, proposed scaling and experimental results. Comments and conclusions will be given at the end of the paper.

2. Materials and methods

The test section was designed to duplicate some of the remarkable characteristics of the aforementioned biological flows. In these conditions, the fluid flows from a relatively large chamber through an orifice. As a consequence, the fluid accelerates suddenly and does not develop a significant boundary layer at the walls. In addition, streamlines rapidly contract at the exit section and a *vena contracta* is found immediately after the orifice. In these ways, real biological flows differ from those generated by means of pipes or piston/cylinder arrangements widely used for the study of vortex ring development.

A sketch of the experimental set-up is shown in Fig. 1. As a result of the reciprocating motion of the piston, driven by the linear motor, the water flowed into the working tank from the inlet to the chamber (cubic, side-length: 40 cm), through a small chamber (cubic, side-length: 20 cm). The investigated flow was generated by a thin-edged orifice (the edge was made sharp all over the border as sketched in the inset of Fig. 1), with diameter $D_0 = 3.0$ cm, located at the centre of an aluminium plate, and was allowed to develop in a 60 cm long and 40 cm × 40 cm wide chamber. Finally, the fluid flowed out from a large, circular, opening (20 cm in diameter) made on a Plexiglas plate. The walls of the tank were made of 2 cm thick Plexiglas. Both the water inlet and outlet were connected to a constant-head reservoir through two one-way in and out valves.