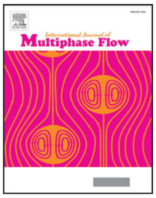
International Journal of Multiphase Flow 79 (2016) 225–235

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow



Liquid flow in a simplex swirl nozzle

Ghobad Amini*

Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada

A R T I C L E I N F O

Article history:
Received 24 November 2014
Revised 31 August 2015
Accepted 12 September 2015
Available online 30 September 2015

Keywords:
Swirl nozzle
Air core
Boundary layer
Spray angle
Discharge coefficient

A B S T R A C T

Pressure-swirl nozzles are widely used in applications such as combustion, painting, air-conditioning, and fire suppression. Understanding the effects of nozzle geometry and inlet flow conditions on liquid film thickness, discharge coefficient and spray angle is very important in nozzle design. The nozzle-internal flow is two-phase with a secondary flow which makes its detailed analysis rather complex. In the current work, the flow field inside a pressure-swirl nozzle is studied theoretically. Using the integral momentum method, the growth of the boundary layer from the nozzle entry to the orifice exit is investigated and the velocity through the boundary layer and the main body of the swirling liquid is calculated. A numerical modeling and a series of experiments have also been performed to validate the theoretical results. The effect of various geometrical parameters is studied and results are compared for viscous and inviscid cases. In addition, the condition in which the centrifugal force of the swirling flow overcomes the viscous force and induces an air core is predicted. The theoretical analysis discussed in this paper provides better criteria for the design and the performance analysis of nozzles.

Introduction

The breakup of a liquid sheet discharging from a pressure-swirl nozzle is an important mechanism in many practical applications such as liquid fuel injection, fire suppression, and air conditioning. Pressure-swirl nozzles are easy to manufacture, have low clogging tendency, provide good atomization quality, and their performance relates to only a few key dimensions. However, the effects of nozzle geometry and inlet flow conditions on the spray behavior are not very well understood.

A simplex pressure-swirl nozzle, in practice, consists of tangential inlet ports, a swirl chamber, a spin chamber, and a discharge orifice (Fig. 1.a). The liquid to be atomized is forced under pressure to enter the nozzle through the tangential ports and, thereby, develops a swirling motion; as a result, a free vortex is developed in the swirl chamber. The swirling motion is intensified in the converging spin chamber while developing an axial flow component, and the liquid is ejected through the discharge orifice. The centrifugal motion of liquid within the swirl chamber creates a low-pressure area near the nozzle exit and forms an air core along the centerline. The liquid then extends into the discharge orifice in the form of a rapidly rotating tube. The rotating liquid is stretched by centrifugal force, and widens in the form of a hollow cone liquid sheet after leaving the orifice (Fig. 1.b). Once the liquid sheet moves away from the nozzle, waves form on its inner and outer surfaces. The difference between the velocity of the sheet and the surrounding gas generates aerodynamic forces that amplify the waves on the sheet. The waves grow in time and space until reaching critical amplitude and cause the liquid sheet to break up (Ibrahim and Jog 2007; Jazayeri & Li 2000).

Pressure-swirl nozzles, in spite of their simplicity, have a complex inner structure. The flow inside the nozzle is two-phase, with secondary flow effects, which make it even more difficult for experimental observation and measurement. The internal flow characteristics in pressure-swirl nozzles govern the characteristics of the sheet formed at the discharge orifice including the velocity components and the sheet thickness. The air core size inside the nozzle plays an important role in controlling the sheet thickness and primary breakup. Authors have frequently observed oscillations on the air core, and claim that these waves induce large variations of the film thickness at the outlet of the nozzle, which may play a role in the atomization process (Chinn, 2009; Som, 2012).

Earlier theoretical studies on swirl nozzles focused on the inviscid analysis (Taylor, 1948; Griffen and Muraszew, 1953). The effects of the orifice length, inlet port length, and swirl chamber length on the nozzle performance were concluded to be insignificant. Taylor also studied the flow inside a swirl nozzle for both inviscid (1948) and viscous (1950) cases. In his inviscid analysis, using Bernoulli's equation and adding an axial flow to a vortex, he calculated air core radius, discharge coefficient, and spray angle. In his next work (1950), Taylor studied the boundary layer flow in a converging swirl nozzle theoretically. He applied a viscous model by assuming that flow domain is divided into two parts: boundary layer and potential core in which

---

* Tel.: +1 519 8884567x38719.
E-mail address: gaminiba@uwaterloo.ca

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.09.004
0301-9322/

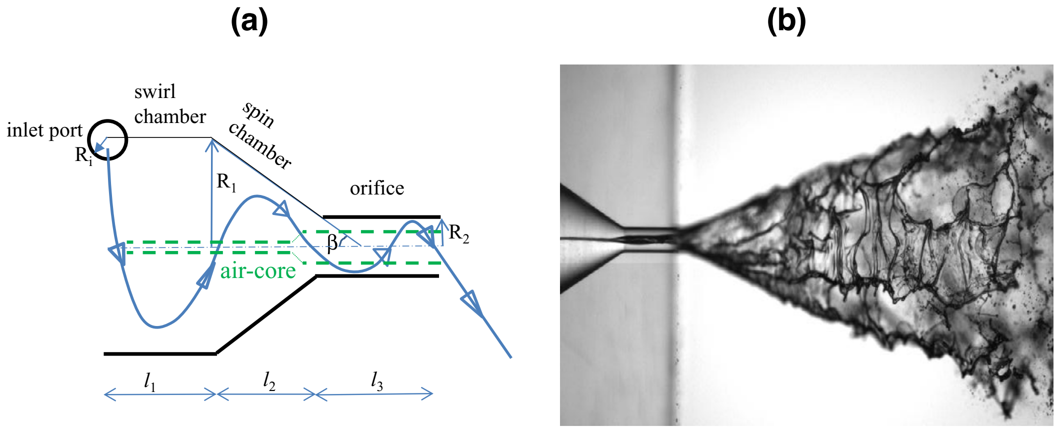


Fig. 1. The schematic (a) and an image (b) of air core and spray formation in a swirl nozzle.

the axial flow exists only in the boundary layer. Taylor assumed that because of the air core formation, the outflow issuing from a swirl nozzle is as thick as the boundary layer itself and concluded that inviscid fluid theory has no application in the fluid mechanics of swirl nozzles. However, the inviscid results may be used as a target for design improvement, and as a bound for real swirl nozzles. Additionally, as concluded by Chinn (2009), for appropriate geometries and liquids, the inviscid theoretical description of the flow field may quite closely describe the real flow found in experiments.

Dumouchel et al. (1992) found that discharge rates given by Taylor's analysis (1950) show some differences from those measured by Doumas and Laster (1953). Dumouchel et al. (1992) showed that the thickness of the boundary layer and the flow rate inside it are both functions of the nozzle design and of the injection pressure. Their computations showed that the thickness of the boundary layer within the liquid film is in the same order of magnitude as the film thickness when the injection pressure of the liquid fuel is small, e.g., in liquid-propellant rockets. They reported that as the radius of the inlet port, the radius of the orifice, and the injection pressure increase, the influence of boundary-layer flow is reduced compared to the bulk flow at the orifice.

Binnie and Harris (1950) followed the approach of Taylor (1950), but assumed that an axial flow component exists in the potential core. The authors compared the boundary layers caused by the swirl with no streaming, and by streaming with no swirl. Where only the swirl velocity is taken into account, the result is identical to the result of Taylor (1950). When only the axial velocity is considered, the boundary layer is thinner than that of the case with swirl and no streaming. By taking into account both the axial and the swirl velocities, the resulting boundary layer calculated by Binnie and Harris (1950) is thin and has almost a constant thickness in most of the convergent part of the nozzle. Furthermore, they considered the effects of surface tension on the air core and showed that the influence of surface tension is negligible.

Pressure-swirl nozzles have been studied experimentally by many researchers (e.g., Doumas and Laster, 1953; Som, 1980; Chenn et al., 1993; Liao et al., 1999; Lee et al., 2010). High-speed imaging has been used extensively to measure the film thickness and spray angle. Most of the research focuses on providing relationships between nozzle geometry, the internal flow field and the external spray characteristics. The experiments were mainly performed in low flow velocities, since the working pressure is limited by the low strength of the transparent nozzle's material, normally made of Plexiglas. Additionally, using Phase Doppler Particle Analyzer (PDPA), droplet size and velocity distribution have been measured (e.g., Belhadef, 2012; Mandal et al., 2008).

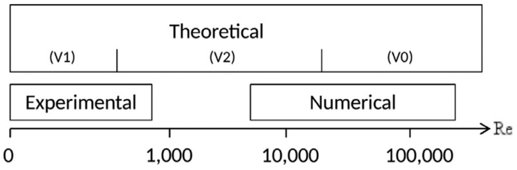


Fig. 2. The operating range of the current approaches; V1: viscous flow assuming no axial flow in the potential core, V2: viscous flow with axial flow in the potential core, V0: inviscid flow.

From a numerical analysis point of view, the main challenge is to accurately describe the liquid–air interface. Capturing the interface through the numerical solution is associated with resolution requirements and usage of considerable computational resources. Depending on the method of capturing the air core location, different algorithms are employed: the Arbitrary-Lagrangian–Eulerian (Liao et al., 1999 and Xue et al., 2004), volume of fluid (Dash, 2001; Ibrahim and Jog, 2007), and level set (Nouri and Kebriaee, 2012) methods. Some researchers ignored the effects of turbulence in the moderate *Re* numbers (Mandal et al., 2008) while others emphasized the turbulence modeling roles (Nouri and Kebriaee, 2012). In general, providing the correct initial-boundary conditions for spray modeling is the main outcome of the numerical solution of the nozzle internal flow.

Understanding the behavior of two-phase flow in pressure-swirl nozzles is highly important to the analysis and modeling of the spray system performance. However, numerical simulation is quite expensive and direct experimental measurement is very difficult due to the small dimensions involved and visibility issues. Therefore, developing a simple yet accurate analytical solution that connects the essential physics of the problem to design parameters is very advantageous. Most of the theoretical work reviewed above covered non-realistic geometries or one-part-nozzle (i.e., spin chamber only), or focused on high viscous and inviscid flows. The main goal of the current work is to provide a theoretical model for nozzle flow by investigating the velocity components in the boundary layer and potential core for a realistic three-part-nozzle operating in a wide range of *Re* numbers. Additionally, the effect of geometrical and flow variables on air core radius (film thickness), discharge coefficient, and spray-cone angle are investigated.

Fig. 2 shows schematically the operating range of the present theoretical, experimental, and numerical approaches. Reynolds number, *Re*, is defined as the ratio of centrifugal to viscous forces at the nozzle inlet. The theoretical approaches V0, V1, and V2 are associated with cases of invsicid, viscous flow neglecting the axial velocity component in the potential core, and viscous flow considering the axial flow