Dynamics of a full-cone atomizing liquid jet

フェルミン, フランコ メドラノ

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氏　　名　：フランコ　メドラノ　フェルミン

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（完全円錐状アトマイズ液体ジェットの力学）

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論文内容の要旨

Liquid jets appear in a vast range of applications. A very active field of application is that of fuel jet injection engines, widely used in the automotive and aerospace industry. Other fields of application include medical apparatuses, so-called “atomizers" used by commercial products in many industries, flows through hoses and nozzles for various industrial purposes as well as fire fighting. In this thesis, we establish original 1D mathematical models for the macroscopic dynamics of a full-cone high-speed atomizing liquid jet ensuing from a circular nozzle into a stagnant gas. Our models, although simple, are shown to compare well with experimental measurements of two- and one-phase jets.

Theoretical research on the dynamics of liquid jets dates back to at least the first half of the 19th century. However, the first one to treat this problem in a hydrodynamic stability sense was Lord Rayleigh (1878) who, for an inviscid jet in vacuum, concluded that the jet was stable to non-axisymmetric disturbances and unstable to axisymmetric disturbances of wavelength greater than the jet's perimeter. Many other early works advanced and improved upon this result. However, these results were focused on what is termed ``primary breakup'', i.e. the transition of the jet from a cylindrical geometry to the formation of the first detached droplets and ``ligaments''. This breakup phenomenon has been found to depend on numerous parameters, and a characterization of the breakup mechanism, based on the dominant physical forces acting on it has been achieved with some success. This has been summarized in what is now called the ``breakup regimes'', of which four have been identified: (i) the capillary or Rayleigh regime; (ii) the first wind-induced regime; (iii) the second wind-induced regime; and (iv) the atomization regime. The range of applications involving atomizing liquid jets forming two-phase fluid flows is still large. Jets of this kind are actually in a turbulent state. The complexity of the atomization process, involving numerous physical phenomena and many variables, ranging from the conditions inside the nozzle (or some generating source) to the interaction between the atomization process and the environment into which the jet is penetrating, all account for numerous challenges in physical and mathematical modeling. Notwithstanding, several mathematical models have been attempted to describe different aspects of the jets in this regime. For example, differential equations for a fuel jet's tip penetration distance as a function of time; models for the gas entrainment rate in a full-cone spray, and a one-dimensional model for the induced air velocity in sprays. None of these models is sufficient by itself.

In this thesis, we propose original 1D mathematical models, based hydrodynamic first principles, for the macroscopic dynamics of a high-speed atomizing liquid jet shaped as a full-cone and discharged from a circular nozzle into a stagnant gas. This kind of jet is a key tool in many industrial processes in modern manufacturing industry, but, as is usually the case with turbulent phenomena, a simple mathematical treatment is unlikely to be available. An advantage of our mathematical models over other analytical 1D models is that ours have only a single main experimentally measurable parameter, the jet-cone angle, while they maintain reasonable predictive power and give theoretical understanding that allows them to deduce other physical quantities of interest. In particular, the local entrainment rate coefficient, K_e, defines the amount of gas entrainment in an atomizing liquid jet. This quantity has been extensively measured for broad experimental settings, as defined from early work on single-phase gas jets and later for two-phase liquid-gas jets. Formulas derived from data fitting or dimensional analysis are available in the literature. One such formula for K_e resulting from dimensional analysis, was introduced by Ricou and Spalding (1961) for single-phase gaseous jets of uniform density, high Reynolds number and originally proposed to be applicable for large distances from the nozzle as compared to the diameter of its orifice, and was later modified by Hill (1972) for uniform velocity across the jet nozzle's exit. Despite being originally formulated for gaseous jets, this definition is also used for the entrainment rate coefficient of (two-phase) atomized liquid jets. To the authors' knowledge however, there is so far no theoretical derivation of it from first principles that is of practical use, although there are some *ad hoc* models available. One of the goals of this thesis is to present this derivation.

Our obtained formula generalizes and reduces to a constant K_e at large distances from the nozzle (far field). An approximation for the near field is also given. Compared to the present study, past models lack a description of the density or liquid fraction of the spray, make unrealistic assumptions or introduce parameters unavailable experimentally. There are also widely used numerical models based on turbulence modeling for jets, like the one by Vallet (2001) used in CFD simulation programs like Star-CD, KIVA-3V, Ansys Fluent, as well as open source codes like OpenFOAM. The present work is mainly concerned with developing analytical models with the advantage of producing closed mathematical expressions. The basic assumptions of our mathematical models are that (i) the jet is statistically stationary and that (ii) it can be approximated by a mixture of a liquid and a gas with its phases in dynamic equilibrium. We derive four related differential or difference equation models by imposing either total or partial conservation of mass, momentum and energy fluxes, which result in analytical, implicit or numerical solutions. The main result is that we can predict the composite mean density and velocity of the two-phase fluid, both as functions of the axial distance from the nozzle, from which the dynamic pressure and gas entrainment rate coefficient are calculated. Assuming a far-field approximation, we theoretically derive a constant gas entrainment rate coefficient solely in terms of the cone angle. Moreover, we report experiments carried out by our collaborators in the Department of Mechanical Engineering, Technical University of Denmark, for a single-phase turbulent air jet. The predictions of our simple models exhibit remarkable coincidence with this and other experimental data of the turbulent phenomena. A critical review of previous fluid-mechanical models is also given, correcting some calculation mistakes in the equations of the cited literature on the way.