THE EFFECT OF NON-NEWTONIAN FLUID AND FLOW CONDITIONS ON THE INSTABILITY OF AN ANNULAR LIQUID SHEET.

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Abstract

A temporal stability analysis was carried out to model the atomization of a swirling viscous non-Newtonian annular liquid sheet emanating from an air-blast atomizer subject to inner and outer inviscid swirling air streams. The dimensionless dispersion equation that governs the instability of a viscous non-Newtonian annular liquid sheet under swirling air streams was obtained. Numerical solutions to the dispersion equation under a wide range of flow conditions were obtained to investigate the effect of the liquid and gas flow on the maximum growth rate and its corresponding unstable wave number. The theoretical behaviour predicted by the dispersion diagrams were compared with the experimental results obtained from the atomization of alginate solution using an air-blast atomizer. It was found that the instability model proposed justify the experimental effects found for the atomization of a non-Newtonian fluid and under the work range for alginate flow rate and viscosity and air flow rate.

Introduction

The process of transforming bulk liquid into a large number of droplets and dispersing them in the form of a spray in a gaseous environment is called as atomization. Liquid atomization is of importance in numerous applications such as fuel injection in engines, crop spraying, food drying, manufacturing of pharmaceutical products, and lately microencapsulation applications [1].

During the last decade atomization techniques as air-blast or twin-fluid atomization has been widely used [2-4]. In air-blast atomization, low-speed liquid jets are accelerated by the surrounding high-speed gas flow, usually in the spray flow direction. The liquid is subjected to both tensile and shearing stresses. The magnitude of the extension has been shown to be significant for applications involving polymer solutions.

Theoretical and experimental studies on the mechanism of atomization have been carried out by Rayleigh, Tyler, Weber, Haenlein, Ohnesorge and Castleman [1]. Detailed reviews of earlier work have been published by Giffen and Muraszew [5], and more recently by Chigier [6], and Lefebvre [1] from these studies it can be concluded that the wave mechanism has been found the widest acceptance among the mechanisms of atomization. According to this theory the disintegration of liquid sheets or liquid jets is caused by the growth of unstable waves at the liquid-gas interface due to the aerodynamic interactions between the liquid and the gas. This type of instability is referred to as Kelvin-Helmholtz instability [7] and is characterized by unstable waves that appear in the fluid interface between two superimposed fluids of differing densities and velocities.

The waves are generated by factors such as pressure fluctuations or turbulence in the gas stream or liquid stream [8-9]. Due to aerodynamic interactions, the perturbations grow in magnitude and reach a maximum value. When the dynamic pressure of the air stream in air-blast atomization is large enough, the amplitude of the surface waves will grow if their wavelength (λ) exceeds a minimum value [8-11]. There exists a dominant or most unstable wave number corresponding to the maximum growth rate and when the amplitude of the disturbance reaches a critical value, the wave detaches from the sheet to form ligaments, which rapidly collapse, forming drops.

E. P. Herrero et. al. [12], based on atomization processes, have developed a new technology of production of microcapsules based on a non-Newtonian fluid alginate solutions, which produced microcapsules ranged between 1-50 microns, with control size and a particle size distribution with a relative span factor, less than 1.4. They have studied the effect of the alginate solution viscosity and flow rate and air flow rate. They have also developed a mathematical semi-empirical model, based on the wave mechanism, to predict the size of the microcapsules produced by atomization [13].

Therefore, the main aim of this work is to develop a temporal stability analysis to model the atomization of a swirling viscous non-Newtonian annular liquid sheet emanating from an air-blast atomizer subject to inner and outer inviscid swirling air streams. The dimensionless dispersion equation that governs the instability of a viscous non-Newtonian annular liquid sheet under swirling air streams will be derived. Usually this equation is derived and solved for an inviscid liquid sheet, because this analysis should be used to improve the fuel atomization in aircraft engines. The elimination of the liquid viscosity in the main equations does not affect very much the solution in this case. However in microencapsulation application, where polymers are used the viscosity can not be eliminated because is a very important parameter especially when the polymer has a non-Newtonian behaviour. For that reason, numerical solutions to the dispersion equation under a wide range of liquid viscosity values, and flow conditions will be carried out to investigate the effects of the liquid and gas on the maximum growth rate and its corresponding unstable wave number. So, the theoretical behaviour predicted by the dispersion diagrams will be compared with the experimental results obtained previously from the atomization of a non-Newtonian fluid, alginate solution, using an air-blast atomizer.

Linear stability analysis.

Sheet instability occurs due to the growth of unstable waves at the liquid gas interface. The growth rates of these unstable waves are governed by fluid properties, nozzle geometry and competition of forces acting on the interface including viscous, pressure, inertial, surface tension, and centrifugal force. There exists a dominant or most unstable wave number corresponding to the maximum growth rate.

A temporal linear instability analysis is conducted to determine the maximum growth rate and the most unstable wave number.

The stability model considers a swirling viscous annular liquid sheet, emanating from an air-blast prefilmer, subject swirling airstreams. Inner gas swirl profile is assumed to be solid body rotation and outer gas swirl profile is of free vortex type. The assumed velocity profiles are similar to the profiles in an air blast atomizer [14].

In the process of determining the disintegration of the swirling viscous non-Newtonian annular liquid sheet emanating from an air-blast prefilmer, the final non-linear dimensionless dispersion equation was derived based on the assumption that the inner and outer gas flows are invisid moving axially outward with swirling velocity components. A complete parametric study has been conducted to insolate the effect of flow conditions and viscosity on the instability of the liquid sheet. The non-dimensional parameters utilized in the final dispersion equation are the axial Weber numbers, *Wel*, *Wei*, and *Weo*, swirling Weber numbers, *Wes*, *Wesi*, and *Weso*, Ohnesorge number, Z, axial wave number *k* , gas to liquid air density ratio, *gi* and *go*, and the annular liquid sheet inner and outer radii ratio, h.

The final dispersion equation does not have a closed form solution and is solved numerically using *Mathematica*™. The Secant method is used where two starting complex guess values are required to determine the roots of the dimensionless dispersion equation. Results from the inviscid case are taken as starting guess values. By varying the value of *k,* it is solved for the root with the maximum imaginary part that represents the maximum growth rate of disturbance corresponding to the most unstable wave number.

Results and discussion.

The frequency with the maximum imagery part represents the most unstable wave that is the perturbation that grows more rapidly than any other and for that reason it dominates the liquid sheet breakup process. Therefore, the most unstable wave number is related to the mean drop size. The growth rate can be related to the breakup length of the liquid sheet. Higher growth rate indicates shorter breakup length. As such the most unstable wave number and the maximum growth rate are two important parameters that will determine the resulting spray characteristics. These parameters are obtained for a number of flow geometry conditions and are discussed below. The results are presented in three graphs (Figures 1, 2, and 3) *w* = *f(k)* called dispersion diagrams. These figures show the expected bell shape, commonly encountered in linear theory analysis. In each situation, a finite range of unstable perturbations, i.e. showing a positive growth rate, was obtained.

a) Liquid flow rate variation:

The influence of the liquid flow rate variation in the growth rate is shown in Figure 1. These results were obtained for an atomization nozzle of 1.8 mm. The experimental conditions were the following: a constant value of pressurized flow air of 138.000 L/min (We_i = We_o = We_{si} = We_{so} = 35128) and the liquid flow rate was modified ranged from 0.003 l/min to 0.037 l/min (We_l = We_s = 0.01 to We_l = We_s = 2). The liquid viscosity was maintained constant at 64.5 mPa s (Z = 0.2). It can be seen in Figure 3 that when the liquid flow decrease, the growth rate increase, which indicates shorter breakup length and smaller drops.

These results are in a very good agreement with the experimental work of E. P. Herrero et. al. [12], where it was found experimentally that the particle size decreases when it is decreased the liquid flow. To justify this effect it should be taking into account that lower values of liquid flow rate result in thinner films. It was observed that thinner liquid films break down into smaller drops.

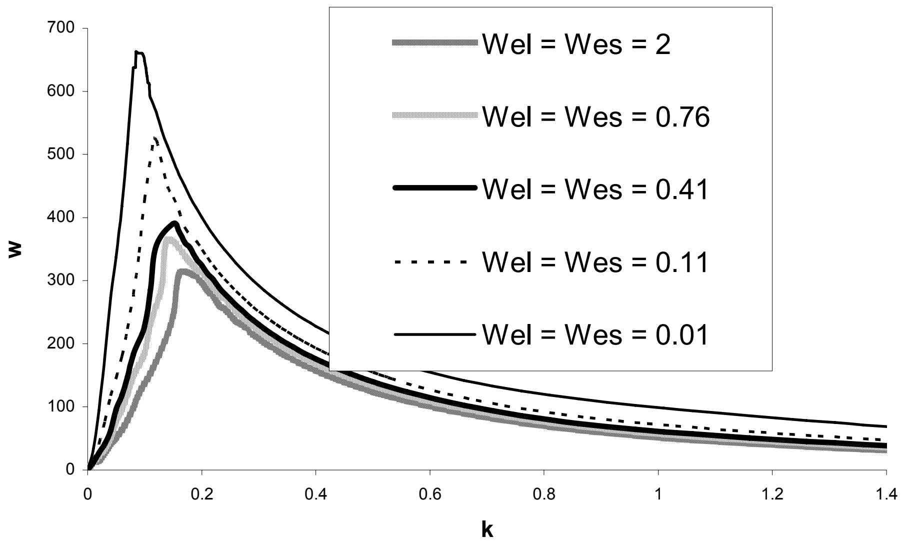

Figure 1: Dispersion diagram at
$We_i = We_o = We_{si} = We_{so} = 35128$; $Z = 0.2$; $We_l = We_s = 0.01 - 2$

b) Air flow rate variation:

The influence of the air flow rate variation in the growth rate is shown in Figure 2. These results were obtained for an atomization nozzle of 1.8 mm. The experimental conditions were the following: a constant value of liquid flow of 0.009 L/min ($We_l = We_s = 0.11$) and the air flow rate was modified ranged from 89.600 L/min to 138.000L/min ($We_i = We_o = We_{si} = We_{so} = 14808$ to $We_i = We_o = We_{si} = We_{so} = 35128$). The liquid viscosity was maintained constant at 64.5 mPa s (Z = 0.2). It can be seen in Figure 2 that when the air flow increase, the growth rate increase, which indicates shorter breakup length and smaller drops.

These results are was found that the particle size decreases when it is increase the air flow. To justify this effect it should be take into account that the liquid/air interaction produces waves that become unstable and disintegrate into fragments. These fragments then, contract into ligaments, which in turn break down into drops.

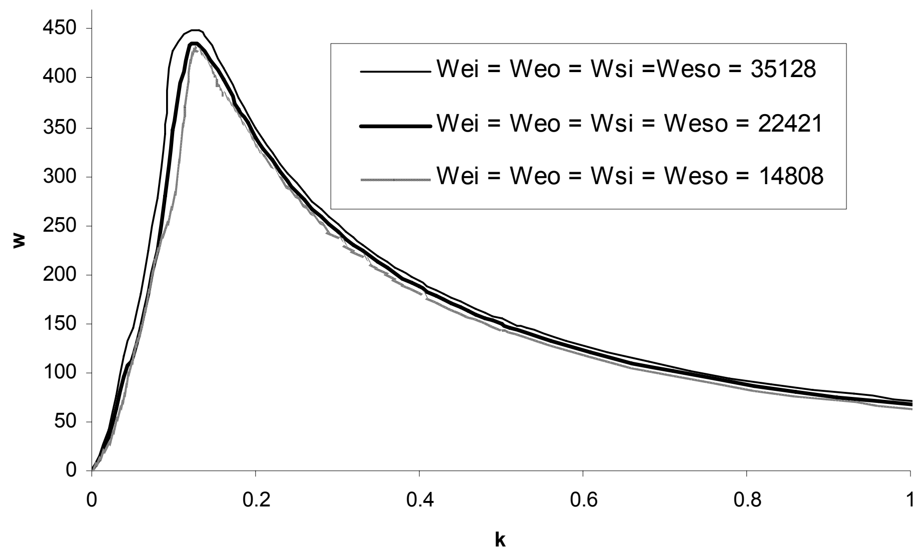

Figure 2: Dispersion diagram at
$We_l = We_s = 0.11$; $Z = 0.2$
$We_i = We_o = We_{si} = We_{so} = 14808 - 35128$

c) Liquid viscosity effect:

The influence of the liquid viscosity in the growth rate is shown in Figure 3. These results were obtained for an atomization nozzle of 1.8 mm. The experimental conditions were the following: a constant value of pressurized flow air of 89.600 L/min ($We_i = We_o = We_{si} = We_{so} = 14808$), a constant value of liquid flow of 0.009 L/min ($We_l = We_s = 0.11$) and the liquid viscosity was modified ranged from 64.5 mPa s to 190.0 mPa s ($Z = 0.2$ to $Z = 0.6$).

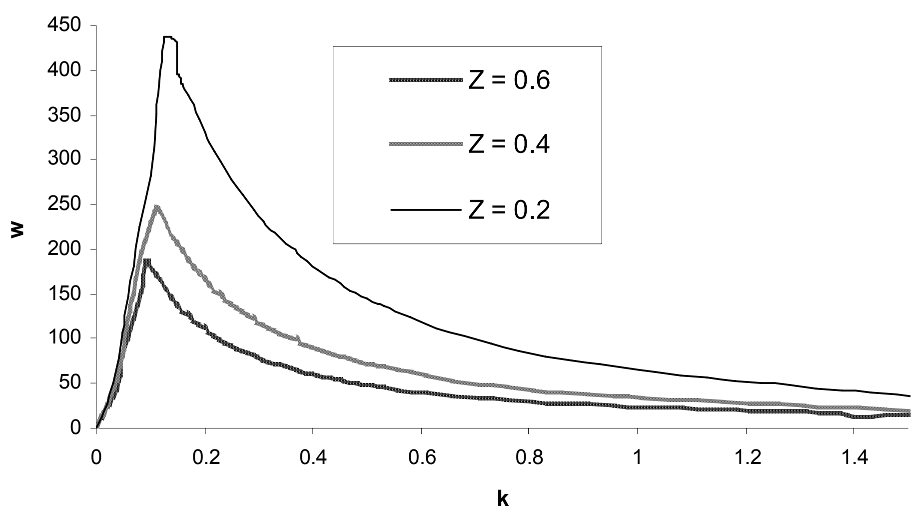

Figure 3: Dispersion diagram at
$We_i = We_o = We_{si} = We_{so} = 14808$; $We_l = We_s = 0.11$; $Z = 0.2 - 0.6$

It can be seen in Figure 3 that when the liquid viscosity decrease, the growth rate increase, which indicates shorter breakup length and smaller drops.

These results are in a very good agreement with the experimental work of E. P. Herrero et. al. [12], where it was found that the particle size increases when it was increased the liquid viscosity.

To justify this phenomenon it should be taking into account that the viscosity of the liquid tends to prevent the growth of the instabilities that cause the rupture of the liquid sheet.

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