

# INTRODUCTION TO LIQUID WALL FILM ATOMIZATION

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**Abstract:** *The objective of the article is an introduction to the theoretical study of atomization of droplets from the surface of a thin liquid film. The overview of basic principles of atomization prediction is complemented by the comparison of the calculations performed according to the selected approaches.*

## 1 INTRODUCTION

Atomization of liquids is a complex problem occurring as a natural phenomenon as well as in a number of technical applications. It can be seen, for example, in the breaking of waves on the sea surface at high speeds of the external air stream, it is an important part of the preparation of fuel in combustion engines or aerosol drug dosage forms. As a side effect, it occurs in piping systems such as turbine engines [8]. The present article is an introduction into atomization of thin liquid wall films.

The phenomenon of atomization is generally part of the problem of hydrodynamic instability, whose foundations were laid at the end of the nineteenth century in connection with the transition of laminar to turbulent flow regime. The instability of thin films has been studied since the mid-20th century. Already, the early works have identified several types of instabilities in the form of various kinds of waves with different wavelengths, phase velocities and geometric shapes. The occurrence of different types of waves is influenced by the film thickness and gas velocity [6], [7]. The atomization of liquid from the surface of the wall film is the final type of instability observed for sufficiently high gas flow rate in two basic geometric configurations. In the case of small diameter pipe the atomization may be cause or effect of the annular flow regime [1]. In experiments of film instabilities in the channel, the atomization was observed in the context of the presence of solitary waves, which are realized for sufficiently low film thickness [19]. The paper pays particular attention to atomization of the thin liquid film on the flat wall.

## 2 EXPERIMENTAL OBSERVATIONS

One of the first experiments of the thin film atomization on a flat plate published Woodmansee [21]. On the basis of the previous experiments and terminology, [11], he uses the term roll waves for solitary waves generated on the surface of the liquid layer or film for relatively high gas velocity. These waves are of large amplitudes and long wavelengths with characteristic geometric progression - a steep front and long rear portions. A geometry model of such waves is proposed by Myia [18]. At gas velocities greater than those required for roll waves, secondary waves arise at the wave crest. These capillary waves are called ripples. They are perpendicular to the axis of the channel (ie the direction of roll waves propagation), their crests are longer than their wavelengths. At supercritical speed of external gas flow, one of these ripples is accelerated and moves toward the front of the roll wave. The central section of the ripple is lifted by the gas stream leaving one or both of the ends connected to the liquid film. This is the primary atomization. The liquid ligament is then secondary atomized into drops. This mechanism has been confirmed by experiments [5] and [9] whose authors further distinguish so-called bag break-up and ligament break-up. Hence, the process is rather more complicated than modeling approach involving an entrainment of the whole part of solitary wave, see eg [15].

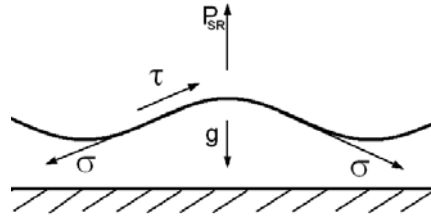
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### 3 THE PHYSICAL MECHANISM

Experimental observations show a direct correlation of the atomization with the liquid film instability, especially with the appearance of roll waves. It is obvious that the physical principle of atomization is linked to the destabilization of the liquid surface leading to waves formation. A review article on the subject gives for example Hanratty [10] or McCready [12].

As in the case of experiments, in the area of physical principles and predictions of entrainment from liquid surface, work of Woodmansee [21] is also significant. The author, in accordance with the principle of the roll waves growth, justifies the process of atomization with imbalance between the stabilizing influence of gravity and surface tension and the destabilizing effects of the pressure drop over the wave crest. This is essentially the Kelvin-Helmholtz instability phenomenon [14].



**Figure 1:** Imbalance of forces acting on the surface.

Since the Kelvin-Helmholtz theory of hydrodynamic instability assumes a uniform velocity profile of flowing air, it is clear that this theory does not explain the physical principle of atomization with sufficient precision for high speed gas flow, when the importance of shear forces increases. Therefore, Kim [13] distinguishes between three types of mechanisms of liquid entrainment, depending on the importance of shear forces. In the case of low gas velocity, pressure forces have the prevailing influence. Kim talks about wave-induced entrainment that occurs on the crest of roll wave due to the force imbalance. The drag force arises mainly due to the pressure drop caused by swirling vortices induced by the boundary layer separation behind the wave crest. As a result liquid bulges are formed and detached by the gas stream. If the gas velocity increases the film thickness decreases and due to small wave amplitudes, the influence of pressure fluctuation decreases and the effect of shear forces increases. In the extreme case where the shear forces are dominant, Kim speaks about shear-induced entrainment. The interface between the two mechanisms is called intermediate entrainment.

### 4 MODELS ACCORDING TO KELVIN-HELMHOLTZ THEORY

From the above it follows that the fundament for modeling the atomization of the film surface is the theory of Kelvin-Helmholtz (further K-H) instability. The power balance of stabilizing and destabilizing forces leads to a condition of neutral stability

$$\hat{P}_{SR} + g\rho_L + \sigma k^2 = 0, \quad (1)$$

where  $\rho_L$  and  $\sigma$  is the density and surface tension of the liquid respectively,  $g$  is the gravitational acceleration and  $k = 2\pi/\lambda$  wave number belonging to wavelength  $\lambda$ . Value  $\hat{P}_{SR}$  is defined as the pressure fluctuation acting on the wave surface

$$P'_S = a \exp(kC_R t) [\hat{P}_{SR} \cos k(x - C_R t) - \hat{P}_{SI} \sin k(x - C_R t)]$$

where  $a$  is the amplitude of the wave described by a relation for the interface displacement

$$h' = a \exp ik(x - C_R t)$$

from the equilibrium thickness  $\bar{h} = h - h'$  depending on the time-space coordinate  $(x, t)$  and phase velocity  $C_R$ , for more see [10].

The Kelvin-Helmholtz solution for the neutral stability condition (1) is obtained by assuming an inviscid plug flow for the gas. Such an assumption leads to the result

$$\hat{P}_{SR} = -(U_G - C_R)^2 k \rho_G, \quad (2)$$

where  $U_G$  and  $\rho_G$  is the gas velocity and gas density respectively [10]. Substituting (2) into (1) and assuming  $U_L \cong C_R$ , the simplified neutral stability condition is obtained :

$$U_G - U_L = \left( \frac{g\rho_L + \sigma k^2}{k\rho_G} \right)^{\frac{1}{2}} . \quad (3)$$

The classic derivation by K-H theory, see [13], leads to the condition

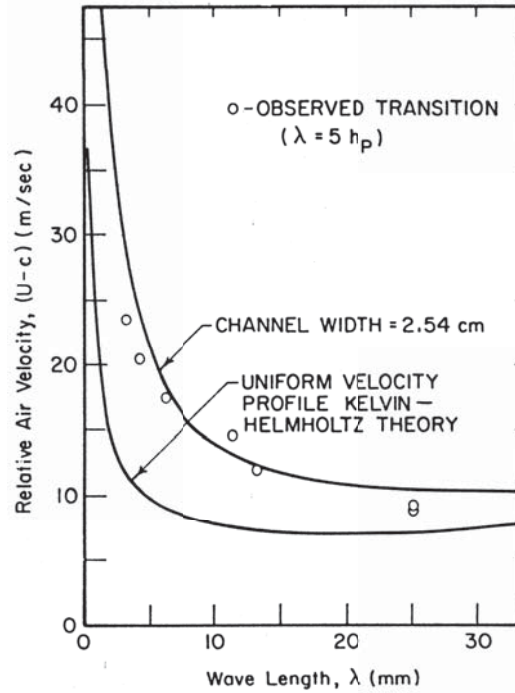
$$U_G - U_L = \left( \frac{[\sigma k^2 + (\rho_L - \rho_G)g](\rho_L - \rho_G)}{k\rho_L\rho_G} \right)^{\frac{1}{2}} . \quad (4)$$

Clearly, from (3) implies (4) for  $\rho_L \gg \rho_G$ . For a water-air interface, the critical value  $U_{Gcrit} = 6.95$  m/s to  $k_{crit} = 17$  mm is received [10]. With regard to the above mentioned deficiencies of K-H theory in relation to debated phenomenon, it is needed to propose advanced treatment of relations (2) and (4).

Woodmansee [21] calculated the pressure displacement  $\hat{P}_{SR}$  assuming the real velocity profile by solving Orr-Sommerfeld equation. He expressed the resulting dependence by the relation that is valid for imperial units only and reads

$$\hat{P}_{SR} = -0.131\rho_G U^2 k \left( \frac{kB}{2} \right)^{-0.627} R_G^{0.229} , \quad (5)$$

where  $R_G$  is the Reynolds number of the gas stream and  $B$  channel height above the surface film. Substituting (5) into (1) the minimum critical velocity is defined by value of 10.8 m/s which better fits the experimental data, see Figure 2.



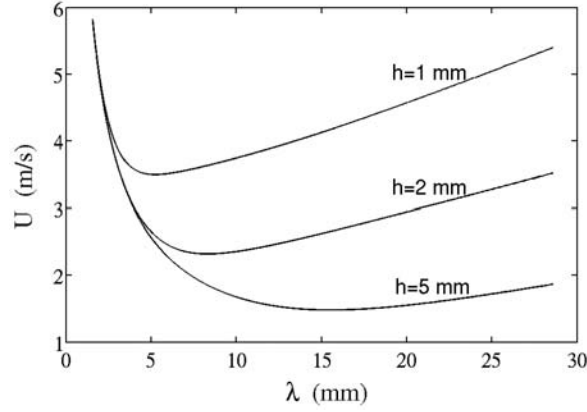
**Figure 2:** Comparison of atomization criterion (1) for pressure amplitude defined by (5) with Kelvin-Helmholtz theory formula (2). Taken from [21].

Two other ways to derive the neutral criteria are outlined Kim [13]. Extending K-H theory by the so-called sheltering hypothesis according to Jeffreys the following relationship can be derived

$$U_G = c + \left[ \frac{4\rho_L c}{C_s \rho_G} \left( \frac{\nu_L k}{\tanh kh} + \frac{1}{4 \sinh^2 kh} \sqrt{\frac{\nu_L kc}{2}} \right) \right]^{\frac{1}{2}} , \quad (6)$$

where  $C_s$  is sheltering coefficient and  $c$  is phase velocity given by formula

$$c = \sqrt{\left(\frac{1}{k}g\frac{\rho_L - \rho_G}{\rho_L} + \frac{\sigma}{\rho_L}k\right) \tanh kh}.$$



**Figure 3:** Critical gas velocity vs wavelength for three depths of liquid flow according to criterion (6) for sheltering coefficient  $C_s = 0.25$ .

Figure 3 shows the critical velocity criterion by (6) depending on the wavelength and the thickness of liquid layer. The experimental data shows that for thickness  $h=2.5-10$  mm and sheltering coefficient  $C_s = 0.25$  the criterion gives velocities of approximately 50% lower than the observed values [13]. Given that the criterion corresponds to the formation of unstable waves, Kim deduces that the origin of these instabilities is not enough to entrain the liquid.

A second explanation for the discrepancy is the limitation of the criterion in such cases where the thickness of the liquid is greater than half of the wave length ( $h > \lambda/2$ ), which is not fulfilled for  $h < 4$  mm. The solution to these disparities may be the option of sheltering coefficient  $C_s$ . A 50% decrease in  $C_s$  leads to an increase in the critical velocity of approximately 40%. However, the author does not provide any method for choosing a particular value.

## 5 MODELS ACCORDING TO ORR-SOMMERFELD EQUATION

In cases where  $h < 1$  mm, the effect of shear forces increases and criteria based on the Kelvin-Helmholtz theory are no longer applicable. Kim [13] has derived the criterion based on Miles article [17]. Using Orr-Sommerfeld (further O-S) equation, Miles derived instability criterion defined with the value of Weber number

$$We = \frac{\rho_L U_s h}{\sigma} < 3, \quad (7)$$

where  $U_s$  is the film surface velocity, which can be eliminated on the basis of shear stress continuity at the interface

$$\tau_i = \frac{1}{2} f_i \rho_G U_G^2 = \mu_L \frac{U_s}{h}, \quad (8)$$

where  $\mu_L$  is the dynamic viscosity of the fluid and  $f_i$  is the interfacial friction factor for wavy anular flow

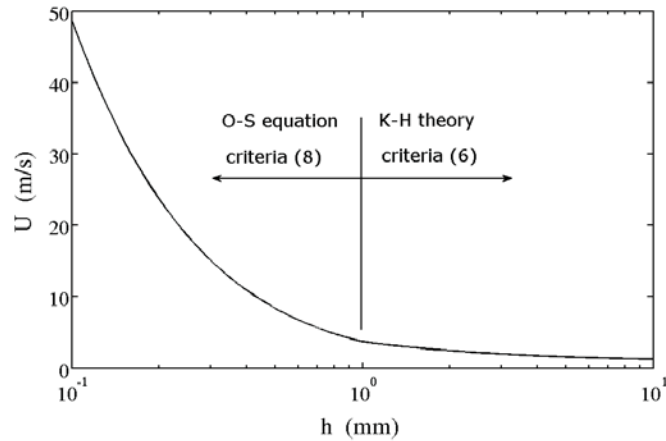
$$f_i = 0.005 \left(1 + \frac{300h}{D_h}\right), \quad (9)$$

where  $D_h$  is the hydraulic diameter. Substituting (9) and (8) to criterion (7) we obtain an expression for the critical gas velocity

$$U_G^2 = \frac{2\sqrt{3}}{f_i} \frac{\mu_L}{\rho_G h} \sqrt{\frac{\sigma}{\rho_L h}}. \quad (10)$$

The two criteria (6) and (10) can be drawn into one graph, see figure 4, if the critical velocities are defined by criterion (6) via their minimum values for the corresponding critical wavelengths depending

on the film thickness. The chart shows that although the criterion (6) is adequate only for the thickness  $h > 2.5\text{--}4\text{ mm}$  [13], the two criteria prove an acceptably smooth connection for  $h = 1\text{ mm}$ . However, the drawback of this criterion (10) is the lack of experimental validation, due to difficulties in measuring small film thicknesses.



**Figure 4:** Critical gas velocity vs liquid depth according to criteria (6) and (10).

Recently, the numerical solution of hydrodynamic instability at the interface of two viscous layers using VOF method has been examined by Zaleski et al. In the article [3], [8], comparison of the VOF method with linear access based on solution of two coupled Orr-Sommerfeld equations assembled for both phases is presented. The solution according to this method is discussed, inter alia, in articles [16], [4], [2], [20]. The critical point of the approach results from the assumptions of Orr-Sommerfeld equation derived assuming linearity for parallel flow. These studies are also limited to mutual validation via numerical approaches without reference to the experimental data.

## 6 CONCLUSIONS

The article is devoted to the introduction of liquid wall film atomization. Experimental data show the relationship between the establishment of various types of instability of the interface and its own primary atomization. The starting point for solving the entrainment of liquid fragments from the liquid film surface is the issue of understanding the origin and development of initial instabilities. The main result of research in this field is the identification of the basic forces affecting the process of entrainment. In the case of thicker layers, the major destabilizing effect is caused by pressure drop in the neighborhood of wave crests. This fact leads to the application of the K-H theory of the hydrodynamic instability. In the case where, as result of higher gas velocity or lower liquid flow rate, the film thickness decreases, the influence of shear forces increases. The appropriate solution under such circumstances is the application of the O-S equation.

The resulting critical velocities based on the K-H theory (1) or (6) depend on the accuracy of pressure fluctuations  $\hat{P}_{SR}$  or sheltering coefficient  $C_s$  respectively. In the case of criterion (10), derived on the basis of the O-S equation, the solution depends on the determination of friction factor  $f_i$ . It follows that solution of shear and pressure forces fluctuations acting on the film surface is essential. In conclusion, there are mentioned approaches of the VOF method and coupled O-S equations based on complex numerical solutions, which both go beyond the introductory nature of this article.

**Acknowledgement :** The article was supported by GAČR under the project GA101/08/0096.

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