THEORY AND OCCURRENCE OF EVAPORATION WAVES

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Abstract. *This paper cites the some occurrences of the evaporation waves and it presents a new generalization of theoretical approach of the phenomenon, commonly applied in one-dimensional problems for three-dimensional cases. Evaporation waves with a two-phase downstream state have been observed experimentally in one-dimensional flow by a number of researches and more recently in other types of flows as in the evaporation jets. A great amount of industrial applications motivates researchers to know the dynamics of the process that involve phase change. The correct behavior of some industrial equipment during operation, guaranteeing the adjusted exploitation of the employed energy and the security of the processes, depend on the correct adjustment of the parameters that govern phase change, aiming at to anticipate the behavior of flashing phenomena and to design and to operate safety and efficiently, boilers, heat exchangers, desalination equipments, steam generators and reservoirs.*

Keywords*. evaporation wave, metastability, iso-octane, Chapman-Jouguet condition, flashing.*

1. Introduction

The correct behavior of some industrial equipment during operation, guaranteeing the adjusted exploitation of the employed energy and the security of the processes, depends of correct understanding of the physics governing phase change. This knowledge is important to anticipate the deportment of flashing and to design better and safety boilers, heat exchangers, desalination equipments, steam generators and reservoirs. Examples could be cited as in the cases of studies in expansion devices of refrigeration cycles, which may be a source of intense noise (Simões-Moreira and Bullard, 2003), or better fuel atomization beyond preheating process (Oza and Sinnamon, 1983). In the 1960s and 1970s, the nuclear industry provided motivation for the study of the flashing phenomenon that could occur in case of rupture of pressurized water pipes. Nuclear power plants have emergency cooling, and safety equipment must be design to remedy reactor loss of coolant accidents – LOCA (Peterson et all, 1984).

It is possible, in some situations, that a pure substance in the liquid state reaches its boiling or saturation point, without a phase transition take place. This condition is reached by the exposition of the liquid to a low-pressure environment, below its saturation corresponding pressure. As a result, the liquid becomes superheated or metastable. The storage and transport of substances in the liquid state (kept to the high pressures) whose saturation pressure is lower than the atmospheric pressure to the normal ambient temperature is common. The disruption of a tank or tubing can lead to a high degree of metastability providing explosive evaporation results (Reid, 1976). The evaporation waves are evaporative phenomena whose occurrence is associated with the lesser degrees of metastability. In this case, the initially subcooled liquid bulk exposed to a large pressure drops is become into superheated liquid and evaporates in a wave-like process (Grolmes and Fauske, 1974; Peterson et all, 1984; Thompson et all, 1987; Hill, 1991; Simões-Moreira, 1994; Simões-Moreira et all, 1993; Simões-Moreira and Shepherd, 1994, 1999; Simões-Moreira, 2000 and Hahne and Barthau, 2000). The evaporation occurs in a narrow and observable interface, characterized by a jump in flow properties proceeding from rapid phase transition phenomenon. It means to say, that the properties downstream and upstream of the evaporation wave are very different. The two-phase mixture formed after evaporation wave continues into the low-pressure region; this process is normally termed in literature by flashing and the evaporation waves have also called, for some researchers, boiling discontinuities or boiling shocks (Labuntsov and Avdeev, 1981, 1982), boiling front propagation BFP (Das et all, 1987), flash boiling or acceleration front by others. The metastable liquid stored energy supplies the evaporation wave with the latent heat of vaporization, necessaries to the continuous adiabatic boiling process. At very lower or inexistent degrees of metastability, simple evaporation occurs as a limiting case with little or no pressure change. Evaporation waves involve mass transfer rates up to 10 or 12 times superior to those due to simple evaporation (Peterson et all, 1984).

2. Occurrence and experimental observations

Over the past four decades many researches has been studied the problem of rapid evaporation. The majority of the experiments let the researchers learn about the depressurization of satured or subcooled liquids and to observe the parameters that cause changes and control the boiling processes.

Shepherd and Sturtevant (1982) and Frost and Sturtevant (1986) verified through photographic documentation the occurrence of evaporation waves in a microscale of butane drops when submitted the metastable limit as represented in Fig. 1a. Emrich (1985) analyzed the expansion of a rapidly moving liquid at radial flow configuration with transition to a vapor or a two-phase mixture of vapor and liquid taking place over a short distance. The Emrich's experiment is shown in Fig. 1b, and it is manly composed by a metal nozzle and a glass plate. The function of the glass plate was to make possible the visualization of the phase change. Liquid $C0_2$ was used like test fluid supplied at saturation pressure at room temperature and it expands from this or other supply pressures to atmospheric pressures. Thus, high-pressure liquid from a supply chamber moves slowly in the 1 mm diameter central core of the nozzle and enters the thin radial flow region between the face of the nozzle and the glass plate. Depending on liquid supply temperature and pressure, nozzle-to-window spacing *"e"* (see Fig. 1b) and the nozzle's shape, it's possible to see the entire center clear liquid, bordered with what Emrich termed "petals" outside and remainder of field cloudy (two-phase mixture), or either, the presence of evaporation wave. The evaporation wave appear because the liquid, during radial flow, is displayed the pressures below of the pressure of the corresponding saturation reaching the metastable state and culminating in an evaporation front.

Hill (1991), Simões-Moreira (1994) and Simões-Moreira and Shepherd (1999) carried out one-dimensional experiments repeated later by Hahne and Barthau (2000). A schematic of the test facility of Simões-Moreira is shown in Fig. 2a.

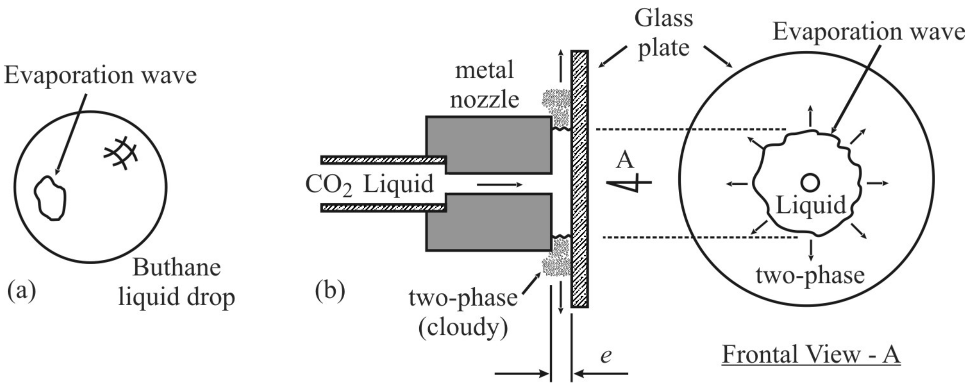

Figure 1. Evaporation waves occurrence examples: (a) in a microscale of butane drop and (b) in a radial flow.

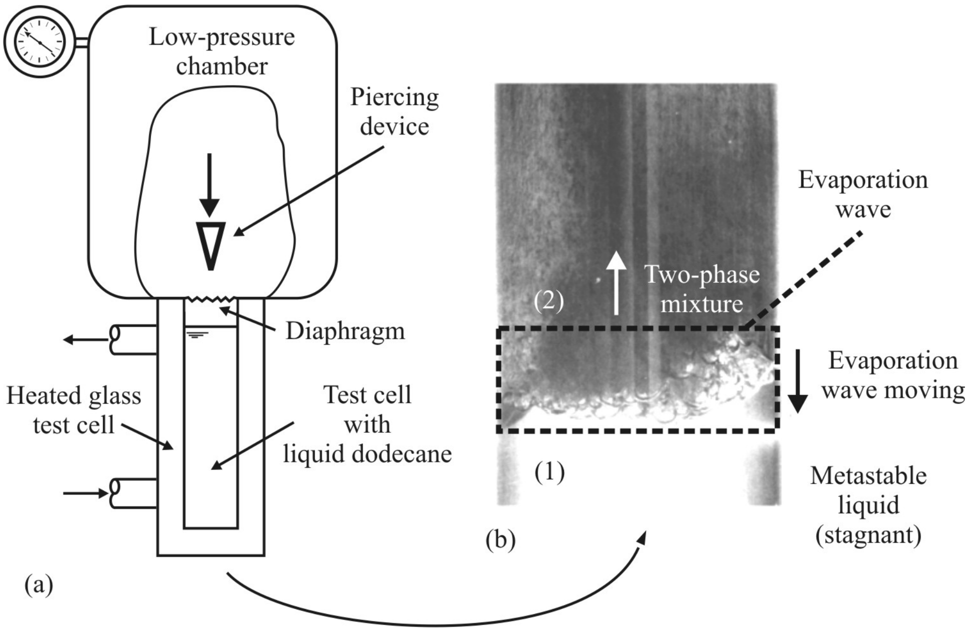

Figure 2. (a) Diagram of test facility and (b) Still picture of one-dimensional evaporation wave in dodecane (Simões-Moreira, 1994)

The main components were a heated glass test cell and a low-pressure chamber. Glass was chosen because its surface is smooth enough to suppress undesirable heterogeneous nucleation and made photographic documentation possible. Circulation of hot air in a square glass jacket partially enclosing the cell was used to heat the system to desired temperature. In its tests, Simões-Moreira controlled the pressure inside the test cell so that the liquid was slightly above the saturation pressure. The low-pressure reservoir was evacuated and the brought up to the desired pressure with N_2 (inert gas), initiating the test with the disruption of the diaphragm.

The still picture of an experiment with liquid dodecane shows in the Fig. 2b reveals a mean evaporation wave region with has well-defined velocity of propagation. The wave is moving from top to bottom and that evaporation front is a highly disturbed region formed by many interconnected hemispherical surfaces that resemble portions of bubbles. After disruption of diaphragm a delay time of 2-3 milliseconds passed until the onset of the evaporation waves. During this time, acoustic waves reverberate within the liquid and a slight cooling took place. Upstream of the evaporation wave it's had a superheated stagnant liquid and downstream of evaporation wave it's formed a two-phase mixture. It's sufficiently reasonable to imagine that fixed all the test conditions and diminishing only the pressure of the low-pressure reservoir the speed of the evaporation wave has the trend to increase. Simões-Moreira (1994) showed that it has a limit for the speed of the evaporation front. From a certain value of pressure of low-pressure reservoir, it does not have increase of speed of the evaporation wave with the reduction of pressure of low-pressure chamber, and the flow is said choked. In these situations (choked flows) the downstream flow travels at the local speed of sound in relation to the moving wave frame. The velocity of two-phase flow is sonic and this makes possible the parallel with the theory and the solution of Chapman-Jouguet of the discontinuities as the deflagration waves in a combustion gas (Simões-Moreira, 1999). The internal energy stored in the superheated liquid plays the same role as the energy stored in the molecular bonds of the reactants.

Simões-Moreira and Bullard (2003) had considered that evaporation waves could appear in expansion devices as short tube orifice or thermostatic valve and to be responsible by a pressure drop and flow chock. Fluctuations of pressure in the expansion devices are cause of intense noise, and the advent of quieter compressors and blowers has made valve noise more noticeable. Figure 3 shows an illustration of the possible occurrence of the evaporation wave phenomenon in expansion devices.

Evaporation jets are other kind of flows where the evaporation wave phenomenon is present, and many researchers had observed and related the fact. Evaporation jets are deriving of the liquid injection beyond nozzles in a low-pressure chamber, which pressure is below corresponding saturation pressure. Experiments with liquid iso-octane (C_8H_{18}) injected in a low pressure chamber through a small conical convergent nozzle have shown the existence of at least three liquid jet regimes: 1) continuous liquid jet, 2) partially atomized, and 3) abrupt liquid evaporation followed by a two-phase supersonic expansion usually terminated by shock waves (highly expanded flashing jet). The last situation occurs at a considerably low back-pressure (Reitz, 1990; Kurschat et all, 1992; Athans and Hirsa, 1995; Simões-Moreira et all, 2002) many times lower than vapor pressure at the initial liquid temperature. This latter case comprises the interest in the present study; therefore it has presence of the evaporation wave.

Figures 4a and 4b show a flashing liquid jet whose images were taken using two different photographic techniques (at a high shutter speed). Figure 1a was taken using the "backlightening" technique and the other figure (Fig. 4b) was taken using the Schlieren technique. It is important to stress that both picture were taken simultaneously.

Careful examination of a series of still pictures (Vieira and Simões-Moreira, 2004) similar to the ones shown in Fig. 4 allows one to conclude that the jet emerging from the nozzle remains in the liquid phase without any perceptible internal nucleation. Images also reveal that the liquid jet exiting the nozzle forms a metastable liquid core seen in Fig. 4a as a shining area and in Fig. 4b as a dark region.

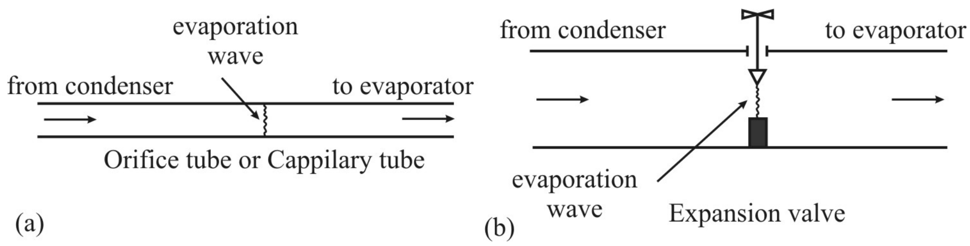

Figure 3. Pictorial illustration of possible occurrence of the evaporation wave phenomenon in expansion devices. (a) orifice tube or capillary tube and (b) expansion valve. (Simões-Moreira and Bullard, 2003).

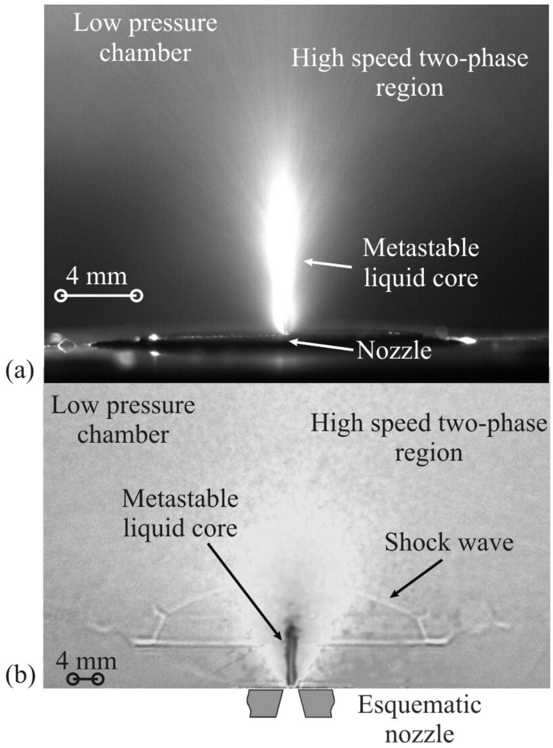

Figure 4. Highly expanded flashing liquid jet – iso-octane; injection pressure 500 kPa; injection temperature 76 ^{o}C; backpressure (low-pressure chamber) 0.11 kPa: (a) "backlight" photography technique and (b) "schlieren" photography technique. (Vieira and Simões-Moreira, 2004).

The confirmation that the jet remains in the liquid phase (liquid core) off the nozzle exit section, can only be obtained using a non-conventional photographic method (high shutter speed). Finally, experimental results (Vieira and Simões-Moreira, 2004) have also indicated that the mass flow rate is upper limited displaying a chocking behavior.

According to the present analysis, flashing takes place on the surface of the liquid core through an evaporation wave process, which usually produces a sonic two-phase flow, but can also be subsonic in less severe conditions (higher backpressure). This sonic state (downstream of evaporation wave) is also a point of maximum mass flow rate given by the Chapman-Jouguet condition. After that, the freshly sonic two-phase flow expands to a high supersonic flow and eventually terminates with the supersonic expansion process throughout a shock wave structure (see Angelo and Simões-Moreira, 2004 for more evaporation jets flow's details).

3. Theory

3.1. Normal evaporation waves

Consider a control volume capturing the steady evaporation wave and moving with it (Fig. 1). The laws of conservation of mass, momentum, and energy can be written respectively as:

$$[J] = \left[\frac{W}{v}\right] = 0\,, \tag{1}$$

$$[P + WJ] = 0\,, \text{ and} \tag{2}$$

$$\left[h + \frac{W^2}{2}\right] = 0\,, \tag{3}$$

where the square brackets indicate a jump in the enclosed value, i.e., $[f] = f_2 - f_1$, v is the specific volume, W is the relative fluid velocity, P is the pressure, h is the specific enthalpy, and J is the superficial mass flux, i.e., the mass flow rate per unit of area. Subscripts "1" and "2" are for upstream (superheated liquid) and downstream (two-phase mixture) states, respectively. By combining equations (1) and (2), one obtains the Rayleigh equation:

$$J^2 = -\frac{[P]}{[v]} . \tag{4}$$

Classical analysis of the Rayleigh equation reveals that the downstream solution lies on a straight line on the *P-v* diagram. It is known that the superficial mass flow rate will first increase as the downstream pressure decreases. This will continue to hold true down to the pressure corresponding to the C-J one. For downstream pressures lower than the C-J pressure, that functional trend will be reversed. Therefore, the C-J point is a condition of maximum superficial mass flow rate. The mathematical statement of maximum superficial mass flow rate is given by $dJ^2 = 0$. Also, it can be proved that at the C-J point the specific entropy jump is also a local maximum as well as a sonic point as informed in the introductory section. It is straightforward to show that, for a given upstream state 1, the condition of maximum applied to equation (4), i.e., the C-J point, results in:

$$\frac{dv_2}{dT_2} = -\frac{1}{J^2_{C-J}} \frac{dP_2}{dT_2} . \tag{5}$$

The downstream specific volume is given by the simple mixture rule $v_2 = (1 - x_2) v_{L2} + x_2 v_{V2}$ (x indicates vapor quality). The subscripts "L" and "V" are for liquid and vapor phases, and the subscript "C-J" was added in order to indicate the solution uniqueness. Implicitly assumed is the hypothesis that the downstream two-phase mixture is homogeneous and is in thermal and mechanical equilibrium. Combining the three conservation equations (1-3), one can obtain the downstream vapor quality, x_2, resulting in:

$$x_2 = \frac{2\left(h_1 - h_{L2}\right) + \left(v_{L2} + v_1\right)[P]}{2h_{LV2} - v_{LV2}[P]} . \tag{6}$$

Where $v_{LV} = v_V - v_L$ and $h_{LV} = h_V - h_L$. Equation (5) can be solved numerically along with Eq. (6) and an equation of state (or a thermodynamic table) valid for the saturation region to obtain the C-J point for a given upstream state. Note that all downstream properties depend only on T_2, given the upstream state 1.

3.2. Oblique and three dimensional evaporation waves

Differently from a normal evaporation wave, in an oblique evaporation wave the main relative superheated liquid velocity is inclined to the evaporating front, as illustrated by the velocity diagram in Fig. 5a. In the case of the evaporation jets the evaporation wave is stationary. The superheated liquid moves at a velocity $\vec{V}_1$ and a tangential plane to the evaporation front and the upstream velocity forms an angle β, which is called the "wave angle". The tangential velocity component is $\vec{t}$ and the normal velocity components are $\vec{W}_1$ and $\vec{W}_2$. The main fluid velocity turns an angle θ as the fluid crosses the wave (θ is the "turning angle"). Oblique evaporation waves have many similar properties to a regular oblique compression shock wave (see Anderson, 1990), which are: 1- the velocities, $\vec{V}_1$ and $\vec{V}_2$, are coplanar with the vectors normal to the wave front (plane α). This means that the fluid velocity bends as it traverses the evaporation wave front but stays in the same plane. 2- the tangential velocity component is invariant across the wave, i.e., $\vec{t} = \vec{t}_1 = \vec{t}_2$. Further implication of this property is that one can transform an oblique evaporation wave into a normal evaporation wave by adding the tangential component to the wave velocity. 3- the stagnation specific enthalpy h_0 is invariant in a stationary oblique evaporation wave, i.e., $h_0 = h_1 + W_1^2/2 = h_2 + W_2^2/2$. On the side of dissimilar properties, the normal component velocity jump $[W]$ is always positive for an evaporation wave. The reason for this is that an increase in the downstream specific volume due to evaporation must be accompanied by a correspondent increase of W_2, as mass flux must be conserved (Eq. 1).

Therefore, evaporation waves accelerate the flow, i.e., $W_2 > W_1$, since $v_2 > v_1$, contrary to the normal component of a regular oblique shock wave. Also, in opposition to an oblique shock wave, the fluid turns away from the evaporation front. Referring to Fig. 5a, the following relationship between θ and β exists:

$$\tan\theta = \frac{\sin 2\beta}{2\left(\sin^2\beta + \dfrac{W_1}{v_2/v_1}\right)} . \tag{7}$$

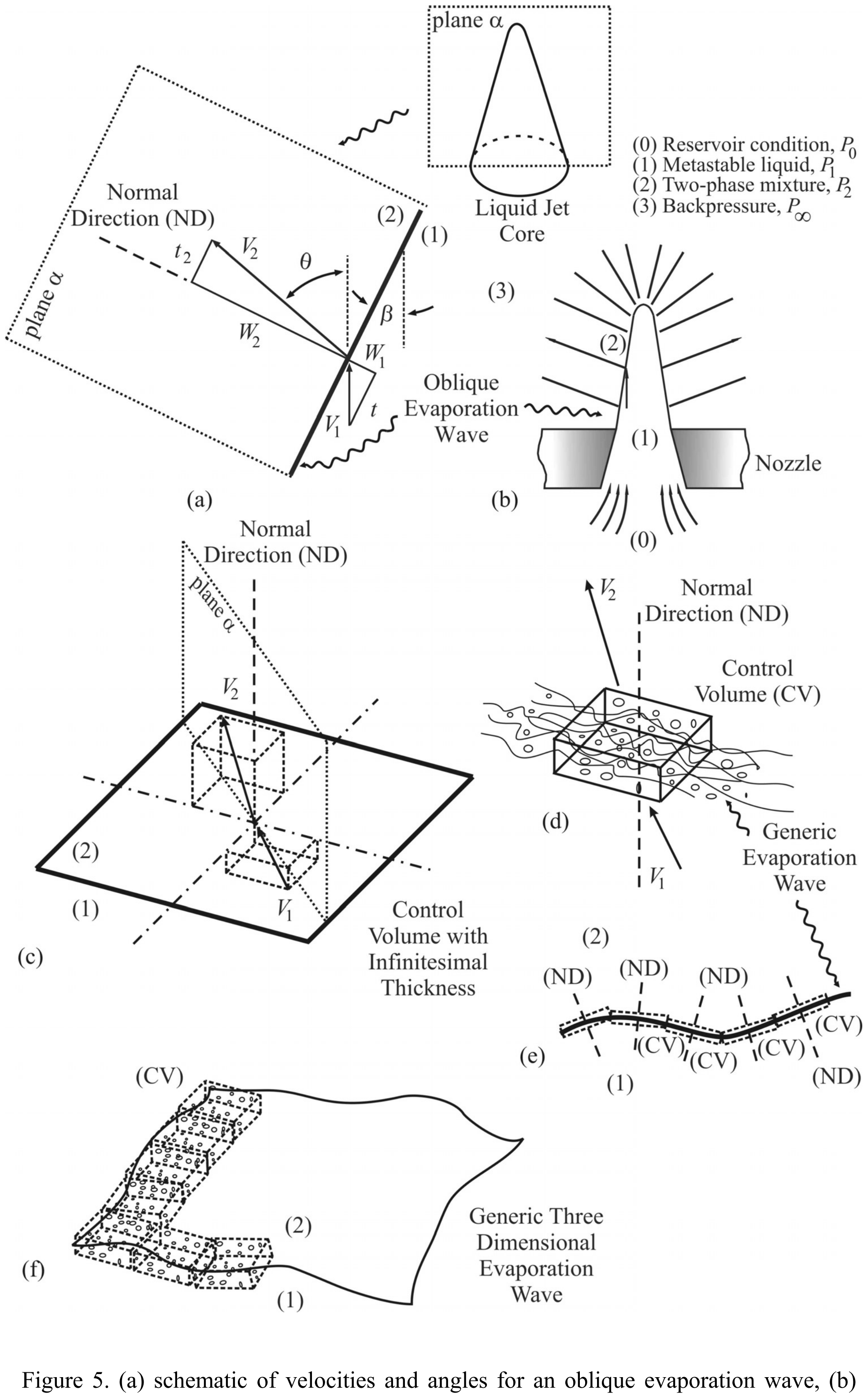

Figure 5. (a) schematic of velocities and angles for an oblique evaporation wave, (b) schematic of the jet stressing the main thermodynamic states, (c) velocity scheme upstream and downstream evaporation wave, (d) control volume detail, (e) a two dimensional evaporation wave and (f) a three dimensional evaporation wave.

Figure 5b shows the position of the evaporation wave for the evaporation jets. Its presence is capable to explain important characteristics of this flow; such which the great evaporation and flow divergence of fluid after the passage for the nozzle and the choked flow condition in some situations (see more details in Angelo, 2004). Other two or three dimensional evaporation fronts (Fig. 5e and Fig. 5f, respectively) can be solved as a finite set of oblique evaporation waves, using the presented jump equations (Eq. (1), Eq. (2) and Eq. (3)). Indeed, it presents a new generalization of theoretical approach of the phenomenon, commonly applied in one-dimensional problems for three-dimensional cases.

4. Maximum evaporation through evaporation wave

It is possible to analyze the condition where maximum evaporation occurs through the evaporation wave. Assuming the simplification $v_2 \cong x_2\, v_{V2}$, because $v_{V2} \gg v_{L2}$, Eq. (7) becomes:

$$\tan\theta = \frac{\sin 2\beta}{2\left(\sin^2\beta + \dfrac{W_1}{x_2\, v_{V2}/v_1}\right)}. \tag{8}$$

Figure 6 shows a wave angle versus turning angle. The downstream and upstream conditions are fixed, chosen for a specific volume rate: $v_{V2}/v_1 = 50$.

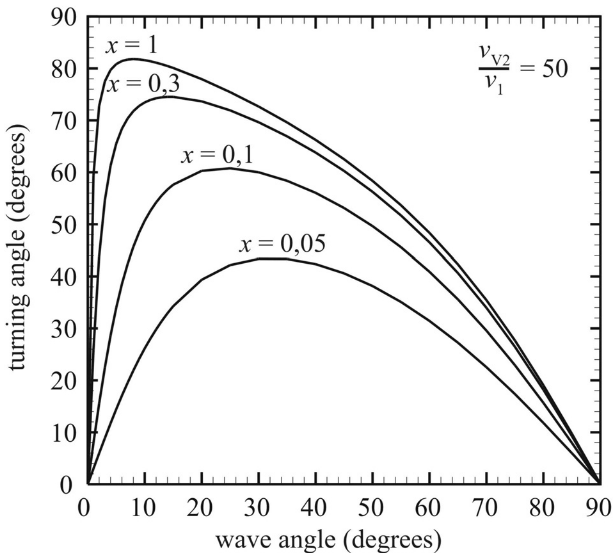

Figure 6. Wave angle versus turning angle (fixed a specific volume rate: $v_{V2}/v_1 = 50$)

Bigger turning angles obtain greater evaporation (higher vapor quality) fixed a same wave angle. This fact can explain why the high evaporation liquid jets diverge immediately at the nozzle exit in the high degree of superheat regime and the droplet cloud around the liquid jet core in some cases could be smaller.

The choice between the multiple mathematical solutions for of the jet liquid core geometry could be solved by use of maximum evaporation beyond evaporation wave. It has experimental evidences that confirm this fact qualitatively (Reitz, 1990 and Vieira and Simões-Moreira, 2004) ant it suggest that a new approach to not solved two-phase superheated jet similar flows could be adopted.

5. Conclusions

Evaporation waves are adiabatic, rapid phase transition phenomenon, which are characterized by a jump in flow properties in a narrow and observable interface. Successful modeling has been achieved by treating the discontinuity in a similar fashion as a deflagration wave. This study presented a new generalization of theoretical approach of evaporation phenomenon, emphasizing the possibility of to calculate the Chapman-Jouguet point for a given upstream superheated liquid state. Evaporation wave phenomena can be observed in some types of phase changing flows when highly superheated or metastable liquid jets are suddenly exposed to a low-pressure environment and explains certain characteristics of this kind of flows.

6. Acknowledgement

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