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Experimental study on the impinging of two opposed inclined electrified laminar jets in the stagnant dielectric medium

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ABSTRACT

This paper presents an experimental study on the liquid column behavior, resulted from impingement of two opposed inclined laminar jets in the presence of high voltage dc electric field. Electric field was generated through two stainless steel capillary nozzles which emit the opposed jets. Distilled water as working fluid of jets and transformer oil as stagnant medium were used in this study. Jets with a collision provide a liquid column which after a short distance its continuity disrupts and droplets is being made. By high speed imaging, the jet column breakup and droplets formation were investigated by observation of surface waves along the column. The effects of applied electric field on the column deviation, its breakup and droplets size formation were analyzed. Results show that increasing of droplets mean diameter and column deviation, but decreasing of droplet formation frequency was obtained by the electric field strength increment. Depend on the wave type on the column surface; twofold breakup behavior will be appearing when the active method of induced electric field of high voltage superimposed.

1. Introduction

The impinging jets (IJ) technique has the subject of many researches in the last two decades because of wide range of its application in industrial processes including evaporative cooling of air [1]; liquid–liquid extraction [2,3]; precipitation and crystallization [4–6]; turbine blade cooling [7]; drying [8]; surface coating [9]; reaction injection molding (RIM) [10,11]; etc. The first patent for this technique was probably published by Carver et al. [12]. The IJ technique was used by Elperin for gas–solid suspensions [13] and further developed by Tamir in various chemical engineering processes [14]. In addition, Mujumdar et al. conducted extensive investigations on the modeling and application of IJ technique in heat-transfer processes [15,16].

A liquid jet emanating from nozzle may breakup to smaller drops when it is subjected to even minute disturbances [17]. These disturbances may be in the form of surface displacement, pressure or velocity fluctuations by passive and active methods.

Linear and nonlinear instabilities of a free liquid jet moving in air and subject to small perturbations are discussed by Yarin and N. Ashgriz [17]. They explain the theories that provide the growth rate of a disturbance wave. The growth rate of the fastest growing disturbance is later used in the atomization theories to obtain a droplet size due to the breakup of a jet. These theories provide an estimate of the main droplet size emerging from capillary breakup. Electric field applying as an active method has been applied in so many fields such as heat transfer [18], electrospraying [19], and mixing [20]. The electrification of the jets has enabled a higher control on droplet forming as the electric forces may change the stability of the jet or the trajectory of the charged droplets created by the jet disintegration. The electrified jet stability has been studied by many researchers [21–28]. Atten and Oliveri [24] showed that the electrification acts on the stability of a jet in a different way depending on the electrical state of the surface of the jet. The response is not the same whether the surface is considered equipotential or nonequipotential. For equipotential situation an increase in electric field or in the velocity or a decrease in the interfacial surface tension destabilizes the jet. This process leads to smaller droplets with smaller breakup length which means that the jet disintegrates closer to injector. They also concluded that the differences in the behavior of both cases can be explained by the distribution of surface charge density. Son and Ohba [29] concluded that in the low electric field strength, the axisymmetric mode has a higher growth rate than that of asymmetric one at all wavelength ranges. With increasing electric field strength, the growth rate of asymmetric mode increases more rapidly and eventually approaches that of axisymmetric mode, also the critical wavelength decreased and the critical growth rate is increased. These mean that the droplet size is reduced and the liquid jet is shortened. Artana et al. [25] reported an increase in spray angle and volume flux density when electric field applied. It is notable that, the electrodes implemented vertically in their experimental

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Nomenclature

D	mean jet diameter (m)
$d(z^*)$	liquid column diameter (m)
g	gravity acceleration (m/s^2)
g_e	effective gravity acceleration (m/s^2)
l	effective gravity acceleration (m/s^2)
L	breakup length in the absence of voltage (m)
L_o	breakup length in the presence of voltage (m)
p	pressure (N/m^2)
p_{st}	hydrostatic pressure (N/m^2)
q	electrical charge density (C/m^2)
Re	Reynolds number
Re_{tr}	transition Reynolds number
u	mean jet velocity (m/s)
$V(z^*)$	liquid column diameter (m/s)
We	Weber number
We_e	electrical Weber number
t	time (s)
T^e	electrical stress tensor (N/m^2)s
T^m	mechanical momentum tensor (N/m^2)
z	distance from impinging point (m)
z^*	dimensionless distance
β	inclination angle
ε_s	surrounding liquid permittivity (F/m)
η	kinematic viscosity
μ	dynamic viscosity
ρ	density (kg/m^3)
σ_j	jet liquid surface tension
σ_s	surrounding liquid surface tension
$\sigma_{j\text{-}s}$	interfacial surface tension

setup, which leads to conclude slight changes in the geometry and mean diameter of droplets size. Huebner and Chu [30] reported that the drops which were formed by an electrified cylindrical jet are smaller than that of droplets which were formed by unelectrified cylindrical liquid jet. They also observe that this discrepancy on drops diameters relates to electrically induced instabilities on the jet.

Despite all these advances on the singular liquid jet and its characteristics, there exist some subtle areas in the laminar region of impinging jets and coherent properties of resulted liquid column, which have not received adequate attention in past. For instance, the influence of imposed hydrodynamic instabilities of impinging on the column and their complex interplay with the electrical perturbations which caused by the novel configuration of electrodes have never been consistently taken into consideration. By this method, the trajectory of jet and produced droplets can be manipulated.

2. Experimental setup and methods

The liquid column behavior resulted from impinging deviated jets in the presence of electric field was investigated experimentally. Characteristics of a liquid column jet, such as breakup length, size of produced droplets, and their formation frequency provides

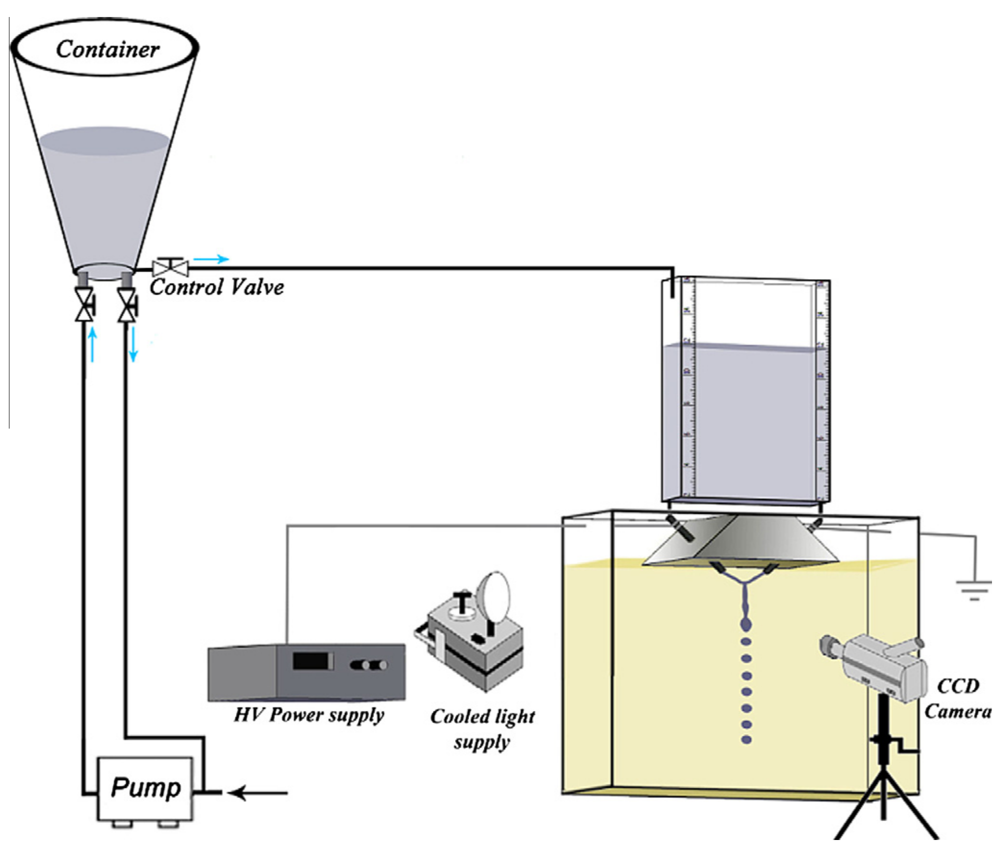

Fig. 1. Schematic layout of experimental setup.