Applied Thermal Engineering 105 (2016) 724–736

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Computational study of mass and heat transport in a counterflowing turbulent round jet

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HIGHLIGHTS

- Round water jet flowing into a uniform counterflow water stream is investigated.
- Presence of a counterflow enhances heat and mass transport of the jet effluent.
- Concentration and temperature profiles are self-similar in the inner region.
- Temperature effect on the concentration decay is presented.

ARTICLE INFO

Article history:
Received 30 November 2015
Accepted 18 March 2016
Available online 26 March 2016

Keywords:
Hydraulic jet
Counterflow
Dispersion
Concentration
Temperature

ABSTRACT

This paper investigates the aspect of a hydraulic round jet issuing into a uniform counterflow under a range of jet-to-current velocity ratios. The prediction of the centerline dilution of jet effluent at velocity ratios ranging from 3 to 15 is performed using the Reynolds Stress Model (RSM). The penetration length is determined by considering the 5% contour of the centerline concentration and compared with empirical relationships suggested by previous researches. A similarity analysis is conducted on the radial profiles of both mean concentration and temperature at successive streamwise stations. The heat transport between the jet fluid and the opposed stream is also investigated with emphasis on the temperature effect on characteristics of the concentration field.

1. Introduction

Turbulent round free jets in a stagnant ambient as well as in a moving external stream have been the interest of numerous investigations for long time. This interest is originated from their practical applications both in industry and in nature. A free jet is a jet issuing into a motionless fluid where no pressure gradients acting on the jet fluid exist leading to the conservation of the jet momentum. However, the interaction between a jet fluid and an external flow leads to a momentum exchange which is relevant to various industrial and environmental problems [1,2]. Three configurations of a free jet discharging in a moving stream, depending on the direction of the ambient flow relative to the jet exit direction, are possible: jets in a coflow, in a counterflow and in a crossflow. Although coflowing jets or jets in a crossflow have been well understood through several advanced investigations in the past, relatively few studies have been subjected to the counterflowing configuration. The comprehension of counterflowing jet behavior is limited by its inherent experimental difficulties together with the pronounced instability of the jet in a counterflow owing to the flow reversal [3,4]. Depending on the jet-to-counterflow velocity ratio $R = U_j/U_0$ (U_j is the velocity at the jet exit and U_0 is the counterflow velocity), two characteristic flow patterns are identified [3,4]; the stable case and the unstable case. At low velocity ratios $R \leqslant 1.4$, the jet region is not developed and the penetration is very small indicating the presence of a stable condition. With increasing R values ($R > 1.4$), the unstable case becomes dominant with a large penetration and random motions of high amplitude. Yoda and Fiedler [4] suggested the division of the flowfield into two distinct parts. In proximity of the nozzle exit, the jet behaves similar to a free jet constituting the potential core region. While in the far field, the behavior of the jet is influenced by the interaction with the counterflowing external stream resulting in the deflection backward of the jet, with further dilution [5]. The jet

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http://dx.doi.org/10.1016/j.applthermaleng.2016.03.090
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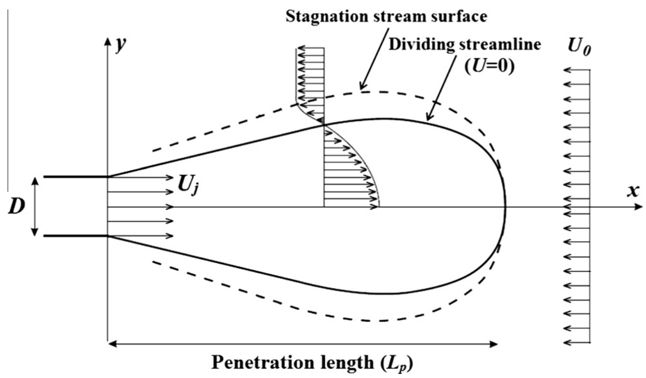

Fig. 1. Flowfield sketch (after Yoda and Fiedler [4], Bernero [5]).

fluid is decelerated by the opposing pressure gradient and its momentum is eventually dissipated producing the jet velocity decay until vanishing at a point referred to as the stagnation point. At this position, the jet is carried away by the counterflow and turned back with high turbulence level causing a rapid and strong mixing of the jet and the surrounding fluid [3]. This faster axial decay along with the enhanced mixing and dilution are the most peculiar characteristics of a submerged jet in counterflow which allow it to be proposed for many engineering fields as for mixing reactors [6] and for wastewater disposal into rivers and coastal waters in environmental applications [1,7]. The maximum penetration of the jet, as defined by Rajaratnam [8], is the point of the stagnation surface at the centerline jet axis, as elucidated in Fig. 1. The distance on the jet axis between the nozzle exit and the stagnation point defines the penetration length L_p (Fig. 1) which is found to be a function of the jet-to-current velocity ratio only [3,4]. Rajaratnam [8] demonstrated that a linear expression lies between the average penetration length and the velocity ratio, with a constant of linearity ranging between 2.4 and 2.7. The same range of linearity is also suggested in Chan [9] and Chan et al. [10] investigations. However, König and Fiedler [3] and Yoda and Fiedler [4] verified experimentally the linearity between L_p and R and they found that $L_p/D = 2.7R$ and $L_p/D = 2.8R$, respectively. Another definition of the penetration length, based on experimental investigation of scalar concentration field of jets discharging into a uniform counterflow, was proposed by Torres [11]. The mean penetration length, among other new length scales investigated in this latter study, is obtained from the 5% contour of the mean concentration field of counterflowing jets in order to generate universal forms of the centerline concentration decay. Torres [11] admitted that data corresponding to the maximum extension of the 5% concentration contour at the jet centerline agree with the linear relationships suggested by Rajaratnam [8] and Yoda and Fiedler [4].

Sweeping into counterflowing jets investigations through the literature, it can be seen that the concentration field had less interest than the velocity field. As well as the decay of the centerline velocity and the growth rate of counterflowing jet mark the jet mixing and spreading efficiency, the concentration field is of a great importance in determining the behavior of penetration, spreading and dilution of round jets developing in a uniform opposing stream. It is found that the presence of a counterflow enhances the mixing of the jet effluent and produces a faster dilution decay compared with a jet in a quiescent ambient [5,7,12]. Yoda and Fiedler [4], Chan [9], Tsunoda and Saruta [13] and Torres et al. [14] assumed that the centerline dilution rate of a counterflowing jet rises when moving downstream and when the counterflow becomes stronger. An analytical model was developed by Yoda and Fiedler [4] based upon the superposition of a free

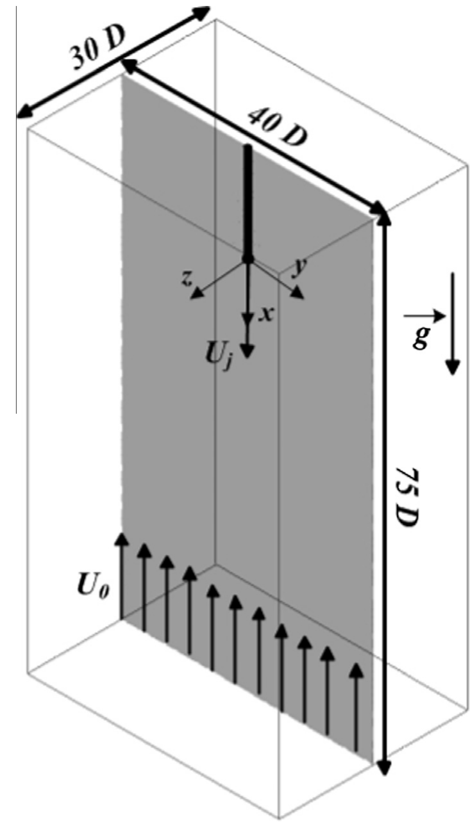

Fig. 2. Flow configuration schematic.

turbulent round jet and a uniform counter-current stream to evaluate the penetration distance L_p. Further, Chan [9] extended this concept to model the velocity and the concentration field of a circular jet in counterflow as the flow field is composed of a forward and a reverse flow where analytical expressions describing velocity and concentration parameters are derived. On the other hand, numerical investigations on counterflowing jets are almost absent, except few studies such as Elghobashi et al. [15], Sivapragasam et al. [16,17], Li et al. [18] and Amamou et al. [19,20]. Elghobashi et al. [15] compared predicted values from numerical analysis of momentum, mass and heat transport of a turbulent air jet in counterflow with their experimental data. Sivapragasam et al. [16,17] introduced some preliminary computational results for a turbulent circular jet flowing into an annular uniform counterflow stream. Li et al. [18] adopted the large eddy simulation (LES) to present visualization and turbulent statistics of a turbulent jet in a counterflow. Recently, Amamou et al. [19,20] conducted a numerical study of a turbulent round jet into a counterflow based on the Reynolds Stress Model (RSM) where velocity and passive scalar fields are investigated.

Although experimental investigations of counterflowing jet clarify its dynamics and its evolution in an approach to control it, further computational studies are necessary to deepen the understanding of the trajectory and the spreading of submerged jet issuing into a counterflow with the aim of generalizing obtained results and getting rid of experiments limitations. For this purpose, a computational study of a turbulent round jet flowing into a uniform counterflow is conducted as an application of toxic pollutants disposal and of chemical species mixing. For example, in a practical case of wastewater discharge into the sea with countercurrents, operational conditions in industry are about $R = 3$ and $Re = 630{,}000$ [21]. The investigation is carried out for different cases of jet-to-current velocity ratios. The Reynolds Stress Model