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A computational parametric study on the development of confluent round jet arrays

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HIGHLIGHTS

- Parametrical study of multiple interacting (confluent) jets.
- CFD simulations are combined with response surface methodology.
- Normalized nozzle spacing, S/d_0, is an important design parameter.
- A Confluent Core Zone without decay of maximum velocity exists.
- Jet deformation occurs in both merging and combined regions.

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ABSTRACT

In this study, Computational Fluid Dynamics (CFD) and response surface methodology is employed in a parametrical investigation of an in-line array of confluent round jets. Confluent round jet arrays are common within several fields of engineering, as detailed knowledge of the flow field development of confluent round jets is of great importance to design engineers working with, for example, chemical mixing, multiple jet burners, waste water disposal systems or ventilation supply devices. In this paper, five independent factors affecting flow field development are investigated with a multi-variable approach using a Box–Behnken design method.

The results include decay of maximum velocity, turbulence intensity, location of merging and combined points and development of volumetric flow rate. Dimensionless nozzle spacing, S/d_0, is an important design parameter and has a large impact on several properties, such as merging and combined points, decay of maximum velocity, and development of turbulence intensity. Other factors, such as the number of jets per row and inlet velocity, are also of importance. The analysis of decay in maximum velocity led to the definition of a new zone of development, referred to as the Confluent Core Zone (*CCZ*), as its behaviour is reminiscent of the potential core of a single jet. The *CCZ* has uniform velocity, lacks considerable decay in streamwise velocity and has a rather low turbulence intensity. The *CCZ* has a characteristic footprint in confluent round jet arrays, and its properties are investigated in detail.

The development of volumetric flow can be divided into two regions. The initial region, close to the nozzles, features a high entrainment but decreasing entrainment rate. As the jets combine, the entrainment rate is lower, but rather constant. While S/d_0 is generally an important design parameter, there is no direct correlation between S/d_0 and entrainment rate of the combined jet.

1. Introduction

A confluent jet is defined as a number of free jets issuing from different nozzles in the same plane and flowing in a parallel direction in which, after a certain distance downstream, they coalesce and move as a single jet [1]. There are several practical applications where confluent jets exist, such as supply devices in ventilation systems [2–4], combustion burners, fluid mixing, multiport waste water diffusers and cooling of devices.

Among different multiple jet configurations, the most attention has been paid to plane twin jets, for which several comprehensive experimental and numerical investigations have been conducted [5–10]. Generally, plane twin jets are divided into three regions: converging, merging, and combined. The converging

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Nomenclature

A_{inlet}	Total inlet area (m^2)
A_{nozzle}	Nozzle inlet area (m^2)
A_{tot}	Total area, one nozzle plate element (m^2)
$C_{1\varepsilon}, C_{2\varepsilon}$	Turbulence model coefficients (–)
C_μ	Turbulent-viscosity constant (–)
d_0	Nozzle diameter (m)
$d_s = n \cdot d_0$	Effective source diameter (m)
D	Scaling length in maximum velocity decay law (m)
E	Edge-to-edge nozzle spacing (m)
h	Nozzle height (m)
H	Height of computational domain (m)
k	Turbulent kinetic energy ($m^2\ s^{-2}$)
K	Decay coefficient, maximum velocity (–)
L	Length of computational domain (m)
ℓ	Length scale (m)
n	Number of jets in each row (–)
p	Static pressure (Pa)
Q	Volumetric flow rate, jet ($m^3\ s^{-1}$)
Q_0	Volumetric flow rate, inlet ($m^3\ s^{-1}$)
$Q_{cp,a}$	Volumetric flow rate at adjusted combined point ($m^3\ s^{-1}$)
Q_i	y-axis interceptor, flow rate combined jet ($m^3\ s^{-1}$)
Re_d	Reynolds number, based on nozzle diameter (–)
S	Centre-to-centre nozzle spacing (m)
S_{ij}	Rate of strain tensor (s^{-1})
T_U	Turbulence intensity (–)
$T_{U,min}$	Minimum turbulence intensity (–)
$\overline{u'_i u'_j}$	Reynolds stresses component ($m^2\ s^{-2}$)
U, u'	Mean and fluctuating velocity component, streamwise direction ($m\ s^{-1}$)
U_i	Mean velocity component in x_i direction ($m\ s^{-1}$)
U_b	Inlet bulk velocity ($m\ s^{-1}$)
U_{core}	Mean velocity in Confluent Core Zone ($m\ s^{-1}$)
U_{max}	Maximum streamwise velocity ($m\ s^{-1}$)
$U_{max,J}$	Maximum streamwise velocity of jet ($m\ s^{-1}$)
$U_{min,J}$	Minimum streamwise velocity between two jets ($m\ s^{-1}$)
V, W, v', w'	Mean and fluctuating velocity components, spanwise (horizontal and vertical) directions ($m\ s^{-1}$)
x	Streamwise coordinate (m)
x_0	Virtual origin (m)
$x_{cp,a}$	Adjusted combined point distance (m)
x_{end}	Location of end of Confluent Core Zone (m)
$x_i = (x, y, z)$	Cartesian coordinates (m)
X_i	ith factor as coded variable
x_{iL}, x_{iM}, x_{iH}	Low, medium and high levels of the ith natural variable
x_{mp}	Merging point distance (m)
x_{start}	Location of start of Confluent Core Zone (m)
y, z	Spanwise (horizontal and vertical) coordinates (m)
y_c, z_c	Coordinates jet geometrical centreline (horizontal and vertical) (m)
y^+	Dimensionless distance from the wall
w	Slot width, plane twin jets (m)

Greek

$\alpha_k, \alpha_\varepsilon$	Diffusion coefficients in turbulence models (–)
δ_{ij}	Kronecker delta (–)
ε	Rate of dissipation of turbulent kinetic energy ($m^2\ s^{-3}$)
ρ	Density ($kg\ m^{-3}$)
ρ_0	Inlet fluid density ($kg\ m^{-3}$)
ρ_∞	Ambient fluid density ($kg\ m^{-3}$)
υ	Kinematic viscosity ($m^2\ s^{-1}$)
υ_t	Turbulent viscosity ($m^2\ s^{-1}$)

Abbreviations

CCZ	Confluent Core Zone
CFD	Computational Fluid Dynamics
CJ	Central Jet
CoJ	Corner Jet
DoE	Design of Experiments
RS	Response Surface
SJ	Side Jet

region includes a recirculation zone with flow reversal between the jets near the nozzles. The free stagnation point, located in the symmetry plane at the end of the recirculation zone, is referred to as the merging point. In the merging region, jet interactions rise and the velocity at the symmetry plane increases until it reaches a maximum, which is referred to as the combined point. In the combined region, the jets form a combined jet that resembles a single jet.

Another multiple jet configuration which has undergone several investigations is the twin round jet. Experimental and numerical investigations on twin round jets has been carried out by [11–16]. The twin round jet share some similarities with plane twin jets. For example the location of maximum streamwise velocity will shift from the nozzle axis to the plane of symmetry between the jets [11].

However, the classifications of different regions cannot be directly transferred from twin plane jets to twin round jets. The strong recirculation that occurs between plane twin jets does not exist between twin round jets (see for example [15]). This means that the merging point definition in plane twin jets, cannot be used for twin round jets. Attempts to define a merging point criteria for twin round jets has been made by [17] (see Section 3.4.1). The combined point of twin round jets, computed as the location where the jets share a common maxima in streamwise velocity at the symmetry plane, has been reported by [12,15]. The results showed that the twin round jets combines further downstream compared to plane twin jets at similar jet spacing. The investigation by [14] showed that higher Reynolds number leads to stronger jet interactions and higher level of turbulent kinetic energy for twin round jets.

Even though arrays of confluent round jets are common in engineering applications, less attention has been paid to this configuration. Analysis of multiple round jets has been conducted within research related to combustion, chemical mixing and ventilation supply devices [15,18,19]. Both experimental and numerical investigations have been conducted on closely spaced jets issuing through turbulence-generating plates in an opposed jet burner [20–22]. The results revealed the existence of three regions: an initial region with constant jet velocity and low velocity between jets close to the nozzle plate, a region dominated by strong jet-to-jet interactions and decay in jet velocity, and finally a region where individual jets can no longer be observed and the turbulence decays. A detailed analysis of multiple jets emerging through a perforated plate has been performed in [23]. Multiple jets impinging on a flat plate has been studied experimentally by [24,25] and numerically by [26,27]. The results show both strong jet-to-jet interactions and symmetry-breaking phenomena within multiple impinging jet configurations.

Entrainment plays an important role in jet development. Multiple unconfined round jets, in which the jets are subject to entrainment from a stagnant surrounding, have been studied by for example [19,15]. For unconfined multiple jets, mutual