CHEMICAL ENGINEERING RESEARCH AND DESIGN 89 (2011) 446–455

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Transport of a passive scalar across a protective wall-jet in a pipe. Part II: Analysis and interpretation

V. Tesař*

Institute of Thermomechanics ASCR v.v.i., Academy of Sciences of the Czech Republic, Dept. of Thermodynamics, Dolejskova 5, 182 00 Prague, Czech Republic

ABSTRACT

First part of this paper (Tesař, 2011) described experimental investigations, combined with numerical flowfield computations, of a pipe flow in which a parallel wall-jet is blown along the inner surface of the pipe. The aim is to separate the main central flow and prevent its contact with the pipe wall. Although originally motivated by the problem of preventing transport of radioactivity to a radiation detector and its activation, the investigations used heat/mass transport analogy so that the actual subject of investigation was transport of heat from warm central air flow across a cool wall-jet flow into the (also cool) wall of the flow containing pipe. This heat transfer is itself also a problem which may be of interest in applications. In the previous part, apart from the description of the experiments, were also presented the basic characteristics of the time-mean velocity and temperature profiles. This second part analyses the obtained combined experimental and computational data to deduce information about general character and intensity of the radial transport across the turbulent protective wall-jets.

Keywords: Protective fluid film; Wall-jet; Heat transfer; Velocity profile; Temperature profile

1. Introduction

There are situations in chemical engineering where fluid flowing in a pipe has to be separated for reasons of safety – if it is chemically aggressive or otherwise dangerous – or for maintaining its purity from the pipe walls. Particularly effective is separation by a concurrent layer of another fluid, because such a layer is permanently renewed. A typical example is flow of a gas so hot – perhaps due to an exothermic reaction – that pipe walls not protected by a layer of cold gas would lose their mechanical integrity. In other cases, a separation by a neutral fluid may be requested to protect a loss of a sample in trace amounts by deposition on the wall. The task of evaluating the effectiveness of the protection is essentially a study of heat or mass transport across the protective wall-jet, e.g., Silieti et al. (2009), Li et al. (2005). Because of the analogy (e.g., Spalding, 1964) between heat and mass transfer, the two tasks are, of course, equivalent in principle.

The motivation for the present investigations was the detection of potential radioactivity of a gas flowing in a pipe past a radiation detector located in the pipe wall. The gas must be separated from the pipe walls to prevent their activation, which would make any subsequent detector readings meaningless. The radioactivity in question was the short-range α-activity, easily shielded off by even a few millimetres thickness of an air wall-jet. The Reynolds number was high enough for the flow being turbulent. The transport by the turbulent eddies across the wall-jet is quite intensive so that the protection cannot be extended over long distances – fortunately, a length of a few pipe diameters is sufficient for placement of the detector.

For safety reasons, the problem was actually simulated by replacing the radioactivity transport by transfer of heat from a warm central air flow across a cool air wall-jet to an equally cool pipe wall. The pipe was of $D = 30.11$ mm diameter. The protective wall-jet issued from a $b = 1.995$ mm wide annular nozzle slit, located at the origin of the axial co-ordinate X_1. All details of the geometry of the test rig are available in the first part of the present paper.

Also the computations were performed for the temperature field. Their agreement with the results of the laboratory experiments were, though not perfect, considered sufficient

* Tel.: +420 2 6605 2270.
E-mail address: tesar@it.cas.cz.
Received 28 July 2009; Received in revised form 25 May 2010; Accepted 29 July 2010
0263-8762/$ – see front matter
doi:10.1016/j.cherd.2010.07.013

Nomenclature

b	nozzle slit width (m)
c_p	Isobaric thermal capacity (J/kg K)
D	pipe diameter (m)
F	surface area (m^2)
$\dot{E}_{T_{wall}}$	thermal power passing into wall (W)
$\dot{E}_{T_{input}}$	thermal power input by the central flow (W)
h	relative temperature difference
$\dot{M}_{X_1}$	nozzle exit mass flow rate (kg/s)
$\dot{M}_{X_2}$	main mass flow rate (kg/s)
Nu	Nusselt number
r	relative radial gradient of temperature
Re	Reynolds number
Re_b	nozzle exit Reynolds number
$\bar{T}$	time-mean temperature (K)
T_{eA}	temperature of the central warm-air flow (K)
$T_{w^{ex}}$	linear temperature extrapolation to pipe wall (K)
ΔT_e	temperature difference across the wall-jet (K)
ΔT_n	extrapolated temperature difference at nozzle exit (K)
ΔT_{in}	temperature increase by heating of the central flow (K)
ΔT_{sub}	temperature difference across the sublayer (K)
u	relative velocity difference (m/s)
v	specific volume (m^3/kg)
w	velocity (m/s)
$\bar{W}_1$	time-mean axial velocity (m/s)
w_a	velocity on pipe axis (m/s)
w_e	minimum velocity in the profile (m/s)
Δw_e	velocity difference across the wall-jet (m/s)
w_m	maximum velocity in the wall-jet profile (m/s)
$w_{\tau w}$	friction velocity at wall (m/s)
X_1	axial position (m)
X_1^*	axial distance from virtual origin (m)
X_1^{**}	axial distance from second virtual origin (m)
X_2^*	radial position measured from velocity maximum (m)
X_2	radial position measured from the pipe wall (m)
X_s	axial position of incipient recirculation
X_{sd}	axial distance of downstream stagnation point (m)
X_{su}	axial distance of upstream stagnation point (m)
y^+	radial friction co-ordinate

Greek letters

α_T	heat transfer coefficient (W/K m^2)
$\delta_{0.5}$	convention scale of wall-jet thickness (m)
δ_m	distance between velocity maximum and the wall (m)
δ_T	convention thickness of the thermal layer (m)
ε	relative energy of turbulent fluctuation
$\eta_{0.5}$	similarity radial co-ordinate for velocity
$\eta_{0.8}$	similarity radial co-ordinate for temperature
φ	area ratio
λ	thermal conductivity (W/K m)
λ_{eff}	effective radial thermal conductivity (W/K m)
μ_e	flow ratio
μ_{ek}	critical flow ratio
ν	kinematic viscosity (m^2/s)

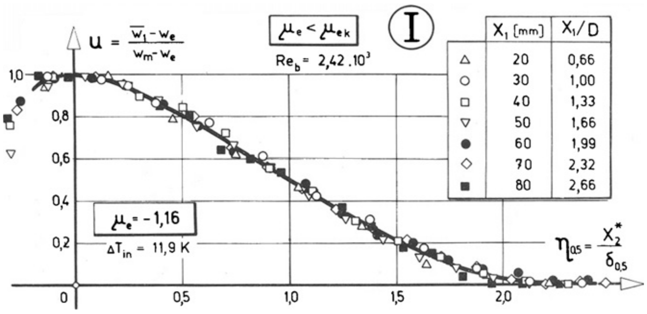

Fig. 1 – Velocity profiles obtained in measurement series I, characterised by relatively slow wall-jet, are here shown to exhibit mutual similarity of the inner layer of the wall-jet. When plotted in the relative co-ordinates, all seven profiles collapsed into practically a single universal curve (cf. also Tesař, 1996a).

for the purposes of the pursued engineering applications. In the experiments, the velocity and temperature measurements were run separately (with different probes). As a result, there were slight differences in the conditions (i.e., not perfectly identical atmospheric temperature and barometric pressure), which were also considered acceptable.

The wall-jet generated by outflow from the narrow annular nozzle along the wall, in parallel with the central flow of warm-air, was found to represent indeed a significant barrier, diminishing heat transfer towards the pipe wall, though not preventing it completely. The presence of such a barrier is reflected by the radial temperature gradient found in the measured temperature profiles at the locations coincident with the inner layer of the wall-jet – i.e., the layer extending inwards from the near-wall velocity maximum.

2. Flowfield in the pipe

2.1. *Apparent similarity of velocity profiles*

Velocity profiles of the wall-jet measured at different positions relative to the flow reversal region generated inside the pipe due to the entrainment into the wall-jet (as shown in Fig. 9 in the first part of this paper (Tesař, 2011) and also discussed in Tesař (2007)) seem to be mutually rather different. It is an important fact, therefore, that the profiles exhibit a mutual similarity of their shapes. When converted to the dimensionless co-ordinates as follows:

(a) the relative radial distance from the wall

$$\eta_{0.5} = \frac{X_2^*}{\delta_{0.5}} \tag{1}$$

where X_2^* is the radial distance measured from the velocity maximum of the wall-jet towards the pipe axis, as shown in Fig. 10 in the first part of this paper, and $\delta_{0,5}$ is the wall-jet half-width, defined also in the same Fig. 10, and

(b) the relative time-mean axial velocity

$$u = \frac{\bar{w}_1 - w_e}{w_m - w_e} \tag{2}$$

where $\bar{w}_1$ is the time-mean axial velocity, w_e is the minimum velocity in a given profile, and w_m is the maximum velocity in the wall-jet, the data points were found to be in all cases on practically the same universal curve, as is documented in the accompanying diagrams Figs. 1–5. Deviations from this