Experimental Thermal and Fluid Science 55 (2014) 86–94

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

An assessment of nozzles for steam attemperation

D.H.C. van Banning[a], C.W.M. van der Geld[a,*], P.J.C. Broos[b], M.-J. Strebe[b]

[a] *Eindhoven Univ. of Techn., The Netherlands*
[b] *Pentair Valves & Control, The Netherlands*

ARTICLE INFO

Article history:
Received 10 April 2013
Received in revised form 14 February 2014
Accepted 15 February 2014
Available online 5 March 2014

Keywords:
Spray
Pressure swirl nozzle
Impaction pin nozzle
Spring loaded nozzle
Discharge coefficient
Drop size distribution

ABSTRACT

With state of the art optical techniques, the drop velocity, drop size distributions, spray homogeneity and spray constancy of three nozzle types have been measured. Inlet water temperature has been varied up to 85 °C. Existing correlations for the exit drop velocity, discharge rate and drop size distributions of various types of pressure swirl nozzles have been examined and adapted for the new data. The resulting expressions are believed to be applicable to this type of atomizers in a general sense. Sprays of spring loaded nozzles are usually both non-uniform and unsteady. The pressure swirl nozzle is found to be robust and at present best suited for steam attemperation. Redesigns of impaction pin nozzles are believed to have potential to prevent wetting of downstream wall area in a wider range of gas flows than with the other nozzle types.

1. Introduction

In many unit operations in the process industry a spray is created. Sprays are in use in the automotive, medical, agricultural and many other areas. A less common application area is a desuperheater which is used for safe and efficient power plant operation. The precise control of the steam temperature is a critical element in such a plant and when that is done by injection of water at a temperature below the steam temperature the process is named steam attemperation or steam conditioning. This process takes place in so-called desuperheaters and two typical steam conditions are given in Table 1. Desuperheaters utilize injection nozzles to inject and distribute water that is much colder than the steam. Naturally, the design requirements of such nozzles are quite severe:

1. Operation at high system pressure and high temperature should be possible.
2. Wear in high-temperature steam at high velocity should be minimal.
3. The nozzles should be thermal shock proof since operation at start-up involves high thermal gradients.
4. Liquid distribution should be homogeneous in order to prevent wetting and wear at pipe walls downstream of the injector.

The latter consideration stems from the fact that the inertia of big drops enables them to cross the gas flow and reach the wall. As a consequence of the above requirements, it is practically impossible to apply moving parts. Nozzles need to be robust in the sense that they possess a long life-time with wear not affecting its performance. Most actual designs of steam injectors in desuperheaters utilize either

- several nozzles flush-mounted in the wall of a steam tube or
- one to three nozzles mounted in a single device that intrudes the steam flow in a pipe.

The system that regulates the water feed is in both cases mechanically as simple as possible. Although nozzles for application in desuperheaters are the focal point of the present study, it will now be argued why it is preferable to first determine the main characteristics of the nozzles in humid air.

Many studies were devoted to the physical mechanisms of spray generation [1,2]. In addition, quite some correlations to design spray generators in practice were published [1–4]. However, many of such correlations appear to be valid for specific nozzle geometries only and/or suffer from a lack of physical foundation.

---

* Corresponding author. Tel.: +31 402472923; fax: +31 402475399.
E-mail address: c.w.m.v.d.geld@tue.nl (C.W.M. van der Geld).

http://dx.doi.org/10.1016/j.expthermflusci.2014.02.019
0894-1777/

Nomenclature

A	area, m^2
C_d	discharge coefficient, –
d	diameter, m
d_{32}	Sauter mean diameter, m
D_s	swirl diameter, m
F	*F*-statistic, –
K_v	velocity coefficient, –
$\dot{m}$	mass flux, (kg/s)
n	distribution parameter, –
P	pressure, Pa
r^2	correlation coefficient, –
Re	Reynolds number, $\dot{m}/(\mu_l d_o)$, –
S	standard error, –
t	thickness, m
T	temperature, °C
u	velocity (cartesian), m/s
u_s	sheet velocity, m/s
Y_d	mass fraction corresponding to diameter d, –
Y_{32}	mass fraction corresponding to d_{32}, –
ΔP	pressure difference over nozzle, Pa
ε	turbulent energy dissipation rate, m^2/s^3
θ	half spray angle, °
μ	dynamic viscosity, kg/(m s)
ρ	mass density, kg/m^3
σ	surface tension coefficient, Pa m

Subscripts

a	ambient
l	spray liquid
o	orifice
p	inlet port
s	sheet/swirl
v	vapor/gas

Table 1
Two typical steam cases for application of the desuperheater.

		Steam case 1 (light)	Steam case 2 (heavy)
Steam properties:			
Pressure, P	(bar)	6	96
Velocity	(m/s)	50	25
Temperature	(°C)	485	590
Mass density, ρ_s	(kg/m^3)	2	25
Dynamic viscosity, μ_s	(kg/m/s)	2.4e−5	3.3e−5
Channel Reynolds number	(–)	8.3e5	5.6e6
Spray water properties:			
Temperature	(°C)	100	185
Mass density, ρ_d	(kg/m^3)	960	890
Dynamics viscosity, μ_d	(kg/m/s)	2.8e−4	1.5e−4
Surface tension coefficient, σ	(N/m)	0.06	0.04

Quite often the designer has to rely on data provided by the manufacturer in order to assess the mean characteristics of a commercial nozzle, which are

- spray homogeneity and constancy in time,
- mean drop size and other drop size distribution parameters and
- discharge range, *i.e.* range of possible mass flow rates for pressure drops that are feasible in common practice.

Not only are these characteristics unknown if the nozzles are made and fabricated according to own designs, as is the case with all nozzles except one measured in the present study. It also makes quite a difference if the gas flow in which the spray is created contains inert gases or not. If a cold drop enters a vapor at saturation condition or a superheated vapor, vapor initially condenses onto the drop while in a later stage the drop evaporates into the vapor at a rate which is mainly temperature controlled. If the gas into which water drops are sprayed contains a large concentration of inert gases and if the partial pressure of the vapor has the saturation value, no evaporation of a drop takes place [5]. In this case drop size distribution characteristics remain approximately constant in the region of the flow where no break-up of drops occurs. With evaporation, the drop diameter changes continuously in flow direction. Inert gases hamper evaporation since the diffusion coefficient of water vapor in air has a small value. This is also one of the main reasons why oceans evaporate relatively slowly. The diffusion barrier by inert gases can be utilized in the definition of a reference measurement to assess spray characteristics.

In the present study it is attempted to minimize drop evaporation in a spray by selecting humid air for the gas flow in which a spray is created. How this is done will be explained in the next section. In the first measurements which will be presented, the measurement location of velocity and drop characteristics have been varied in order to examine the changes in flow direction. Next, two reference distances to the nozzle are defined which are used to measure spray characteristics. The choice of these distances will be shown to be much less crucial in humid air than in vapor.

Several nozzle types will be examined, and all nozzle types except one are robust in the sense that they satisfy the above design criteria 1, 2 and 3 and are own designs of Pentair Valves & Control. The knowledge that they are robust has been gained during about 25 years of experience with these nozzles in steam attemperation applications. The only exceptional nozzle type is one with a more intricate geometry which has not been tested in desuperheaters; it has been selected for this study because of its potential to create small drops. Comparison will be made between the performances of all nozzle types. Since the same reference distances are used for all nozzles, comparison is appropriate and fair. Amongst other things, the satisfying of the above design criterion 4 will be tested.

The inlet water temperature will be varied up to 85 °C in order to vary the surface tension coefficient in a considerable range. Correlations for spray characteristics from the literature will be examined for their potential to predict trends in the new measurements. Drop-size correlations are commonly believed to be too many and too much related to specific cases. For this reason the applicability of existing correlations is thoroughly tested. If necessary, the correlations will be adapted to fit the data. The fact that the nozzles tested are of familiar types but are own designs is considered to offer a challenging and interesting test of existing correlations. The main goals of the correlations to be presented are to

1. facilitate the design and selection of nozzles,
2. provide start conditions for CFD computations of trajectories of drops sprayed into a channel,
3. provide reference data for future measurements of spray generation in vapor.