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Energy considerations in spraying process of a spill-return pressure-swirl atomizer

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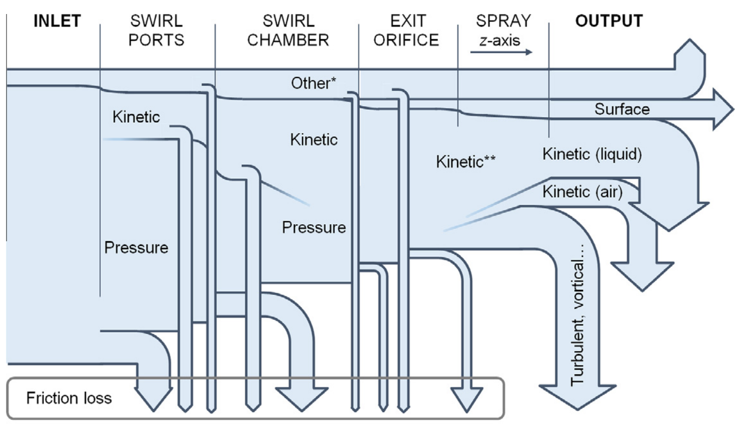
HIGHLIGHTS

- We analyse energy conversion in simplex and spill-return pressure-swirl atomizer.
- Inlet (pressure) energy converts into liquid motion with nozzle efficiency ~58%.
- Kinetic energy of developed spray at closed spill line is ~33% of the inlet energy.
- It consists of energy of droplets (~2/3) and entrained air (1/3).
- Atomization efficiency is <0.3%; it declines with inlet pressure and spill opening.

GRAPHICAL ABSTRACT



*kinetic, gravitational, acoustic, thermal and other energy forms
**in axial, radial and tangential direction, turbulent, vortical etc.

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ABSTRACT

The work focuses on energy conversion during the internal flow, discharge and formation of the spray from a pressure-swirl (PS) atomizer in the simplex as well as spill-return mode. Individual energy forms are described in general and assessed experimentally for a particular PS atomizer and light heating oil as a medium. The PS spray was observed at various loads to investigate the liquid breakup process and the spray characteristics. Spatially resolved diameters and droplet velocities, measured by means of phase-Doppler anemometry, served for estimation of the energy characteristics in the PS spray.

The input energy given by the potential energy of the supplied liquid partially converts into the kinetic energy (KE) in the swirling ports with hydraulic loss in per cent scale. Most of the pressure drop is associated with rotational motion in the swirl chamber with total conversion efficiency at the exit orifice ~58%. The rest of the input energy ends up as friction loss, leaving room for improvement.The overall value (ID_{32}) of the Sauter mean diameter of droplets in the spray, D_{32}, varies with pressure drop Δp_l powered to −0.1. The radial profiles of D_{32} widen with the increase in spill/feed ratio (SFR), but the ID_{32} remain almost constant within the studied SFR range. The spray KE at closed spill line covers the droplet KE (21–26%) and that of entrained air (10–13%), both moderately varying with Δp_l. The specific KEs of both the liquid and air markedly drop down with the spill line opening.Atomization efficiency is less than 0.3% for the studied range of operation regimes and depends on Δp_l and SFR. Our results confirm low power demand of simplex PS atomizers, with extra energy consumption in spill mode. Several

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recommendations are given for PS atomizer innovations and development of new, more efficient, designs meeting more stringent environmental requirements.

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Nomenclature

A	interfacial area, cross-sectional area (m^2)
a, b	coefficients in Eqs. (2) and (5) (–)
b	width (m)
c	specific heat capacity (J/(kg K))
c_w	velocity coefficient (–)
D	droplet diameter (μm)
D_{32}	Sauter mean diameter, SMD (μm)
d	diameter (m)
E	energy (J)
e	energy, represented as percentages of the total input energy, specific energy (%, –)
f_D	Darcy friction factor (–)
h	height (m)
ID	integral (overall) droplet diameter (μm)
k_{p1}	width to length ratio of swirl ports (–)
k_{p2}	length to width ratio of swirl ports (–)
L	breakup length (mm)
l	length (m)
m	mass (kg)
n	number (–)
$\dot{Q}$	volumetric flow rate (m^3/s, ml/s)
Re_W	Reynolds number according Walzel [34] $(= (2\rho_l \Delta p_l)^{0.5} d_o/\mu_l)$ (–)
r	radial distance from atomizer axis (mm)
T	thermodynamic temperature (K)
t	film thickness (m)
V	volume (m^3)
We	Weber number, $(We_g = \rho_g (w_l - w_g)^2 D/\sigma)$ (–)
w	velocity (m/s)
x, y, z	Cartesian coordinates (z = axial distance) (mm)

Greek characters

α	spray cone angle, SCA (deg)
Δp_l	pressure differential between the atomizer inlet and exit (MPa)
ε	spill/feed ratio, SFR, $(= V_{ls}/V_{li})$ according [6] (–)
η_a	atomization efficiency (%, –)
η_n	nozzle efficiency (%, –)
μ	dynamic viscosity (kg/(m s))
ρ	density (kg/m^3)
σ	liquid/gas surface tension (kg/s^2)

Subscripts

A	surface
c	swirl chamber
D	droplet
g	gas, ambient air
i	inlet, index number
j	index of measurement position
k	kinetic (energy)
L	in the breakup distance
l	atomized liquid (light heating oil, LHO)
o	exit orifice, outlet
p	swirl ports
s	spill-return

1. Introduction

Atomization of liquids is a process during which bulk liquid is transformed into fragments or small droplets; the process is accompanied with a significant increase in the interfacial area and consumes the energy introduced to the liquid at the atomizer inlet. The nature of the feed energy[1] determines the atomization process. Thus, from the energy point of view, an atomizer can be considered a device that converts the input energy, E_i, into the increased surface tension energy of sprayed liquid, E_A. Effectiveness of the conversion is characterized by the atomization efficiency: $\eta_a = E_A/E_i$. Its knowledge allows comparison of different types of atomizers and improvement of the spray quality. The quality of the atomization process is frequently described using the Sauter mean diameter (SMD or D_{32}) [1] of the final droplets in the spray; the smaller the SMD the better the spray is. It is crucial namely in combustion applications; the SMD of a sprayed fuel strongly affects the combustion process, namely the stability limits, combustion efficiency and pollutant emission levels. Good atomization quality promotes the fuel evaporation and decreases the demand of ignition energy [2]. A properly designed atomizer is thus a prerequisite for efficient combustion and optimal use of energy resources through proper utilization of the chemical energy contained in expensive fossil liquid fuels.

Bayvel and Orzechowski [3] show all traditional atomizers work with very small η_a, typically below 0.1%, and that any spray quality improvement requires disproportionally more energy as η_a drops down. For example, a pressure atomizer generating 100 μm droplets has η_a = 0.05–0.07% and to reduce the diameter to 50 μm causes the efficiency to drop to the order of several thousandths per cent. Rivette and Evers [4] calculated atomization efficiencies of compound pressure nozzles ranging from 0.4% to 1% according to the injection pressure. They observed that increasing the velocity of the fluid is an increasingly inefficient method of creating the turbulence necessary for drop formation. Dumouchel et al. [5] also studied compound nozzles and found their atomization efficiency in range 0.9–2.6% depending on their design rather than on injection pressure. Loefler-Mang and Leuckel [6] investigated the atomization process of spill controlled pressure-swirl (PS) atomizers and found remaining surface energy of droplets between 0.1% and 0.4% of the initial static pressure energy. Petela [7] applied an exergetic approach to the pressure and airblast atomization. He found the exergetic efficiency of the pressure atomization for inlet pressures in the order of 0.1–1 MPa is below 1% and it decreased with the growth in the inlet pressure. Sovani et al. [8] compared the performance of a conventional pressure injector with an effervescent Diesel injector (DI) designed for fuel injection into Diesel engines. They found the pumping energy required for delivering fuel with their effervescent DI operating at an injection

[1] It is either the potential energy of the liquid in pressure atomization, the electric energy for ultrasonic and electrostatic atomizers, or the mechanical power for rotary atomizers etc.

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