Chemical Engineering Science 66 (2011) 1622–1630

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Rapid quenching by supersonic expansion and injection of water

T. Rakel *, K. Schaber

Institut für Technische Thermodynamik und Kältetechnik, Karlsruhe Institute of Technology, Engler-Bunte-Ring 21, 76131 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 17 May 2010
Received in revised form
26 November 2010
Accepted 16 December 2010
Available online 22 December 2010

Keywords:
Quench
Supersonic
Design
Evaporation
Multiphase flow
Particle processing

ABSTRACT

Gaseous components or gasborne particles in flows are often sensitive to mid range temperatures, whereby unintended side products or aggregated particles develop during cooling processes. Supersonic quenching combines high gasdynamic cooling rates of $dT/dt < -10^6$ K/s with a total enthalpy reduction through evaporation of an injected liquid. In this manner the residence time at critical temperatures is minimized. Up to now there are no publications covering this particular application. Preliminary test results regarding the massive water injection into a supersonic laval nozzle flow are presented as well as the developed supersonic quench concept and corresponding design rules. Essential is the suppression of an anew temperature rise downstream of the supersonic domain when the gas is compressed and decelerated again. Therefore liquid injection into the supersonic domain and its partial evaporation within it is a key feature. Despite the massive water injection the gas flow must remain in a supersonic regime. In addition to water injection from the wall a moveable slender cone equipped with water jets is extending into the divergent nozzle from the exit to enhance the coverage of the cross-sectional area with dispersed water. Presented experimental results in form of pressure and temperature profiles prove the functional efficiency of the supersonic quench. Pressure profiles attest the supersonic conditions downstream of the water injection and define the supersonic domain length. Two dimensional temperature plots demonstrate the sufficient water distribution, the suppression of hot subsonic zones and the total evaporation of the injected water within the quench domain. Applied to "Gasdynamically induced nanoparticle synthesis" spherical non-aggregated nanoparticles are obtained.

1. Introduction

High cooling rates are of special interest in various engineering applications, especially with regard to unintended processes taking place at critical mid range temperatures. Synthesis gas production and flue gas treatment are two typical processes with occurring side reactions at mid range temperatures. In the former case mid range temperatures decrease the recovery in the latter exhaust limits of toxic substances can be exceeded. Another temperature dependent phenomenon is the growth of nanoparticles. At critical mid range temperatures nanoparticles form hard aggregates due to sinter effects. Thus an effective quenching system is characterized by low residence times in the critical temperature range.

Within the scope of the project "Gasdynamically induced nanoparticle synthesis", funded by the Deutsche Forschungsgemeinschaft (DFG), a novel supersonic quenching system was developed. The project goal is the production of non-aggregated oxide nanoparticles with a narrow particle size distribution. The reactor concept differs clearly from known industrial production processes like flame synthesis (Wegner and Pratsinis, 2003) or hot-wall synthesis. But nevertheless it is a high throughput reactor with gas flow rates up to 100 g/s. The reactor consists of two consecutive laval nozzles with a reaction zone in between and utilizes the high gasdynamic heating, respectively, cooling rates. A detailed process description is given by Grzona et al. (2009). This paper describes the quenching of a pressurized hot gas flow with dispersed nanoparticles in order to stop particle growth instantly.

A supersonic water quenching system combines a laval nozzle and a quenching system with water injection and evaporation in one setup. Within the divergent convergent laval nozzle a hot gas is accelerated into a supersonic regime and subsequently water is injected. To the knowledge of the authors this is a completely new application, which has not been published in literature until present. Regarding the substeps numerous results have been published. Supersonic compressible flows have been widely studied in the course of aeronautical and aerospace engineering. The dynamic and thermodynamic contexts are considerably described by the works of Anderson (2004) and Shapiro (1976). Publications utilizing and investigating the high gasdynamic cooling rates in process engineering are rare. Mayer et al. (2004) used different laval nozzles to vary cooling rates of a nanoparticle loaded hot gas flow. They found a decreasing agglomerate size with increasing cooling rates, but sintering could not be suppressed. This is probably due to the fact, that the total enthalpy of the gas was neither indirectly nor directly reduced.

An essential parameter for a supersonic quench design is the liquid injection. Liquid jet atomization has primarily been investigated for propulsion systems, ramjet and scramjet combustors. Due to the high

* Corresponding author. Tel.: +49 721 608 5458; fax: +49 721 608 2335.
E-mail addresses: thomas.rakel@kit.edu (T. Rakel), karlheinz.schaber@kit.edu (K. Schaber).

0009-2509/$ - see front matter
doi:10.1016/j.ces.2010.12.027

gas velocities there is a widespread consensus to use traverse single phase nozzles for this purpose. In these combustion systems atomization and mixing with the air are of prime importance to reduce pollutant emissions and increase combustion efficiency. A general overview on supersonic combustion is given by Billig (1993), whereas investigations on supersonic combustion of traverse injected kerosene jets are presented by Gruenig and Mayinger (1999) and Yu et al. (2002). There are various publications on crossflow injection. Besides a detailed investigation on breakup processes of liquid jets in subsonic crossflow Wu et al. (1997) presented a comprehensive literature review. The overall performed studies analyze spray appearance, jet penetration, velocity fields and near-field structures to develop a fundamental understanding of occurring jet breakup mechanisms. In general the continuous jet breaks up into bigger ligaments which further disintegrate to droplets. Shearing-off droplets from the liquid column is indicated as surface breakup. In cases dominated by aerodynamic forces the primary jet breakup is in principle comparable to secondary droplet breakup processes. With increasing gas momentum fluxes the aerodynamic secondary breakup merges with the primary breakup, whereas the drop size decreases simultaneously. Furthermore at high gas phase momentum fluxes the liquid jet undergoes column breakup without significant surface breakup (Wu et al. 1997). Droplet sizes and cross-sectional mass fluxes were investigated for liquid jets in subsonic crossflow with Mach numbers between 0.2 and 0.4 by Wu et al. (1998). A numerical study of crossflow injection at gas turbine conditions with comparison to experimental results regarding trajectory, volume flux and sauter mean diameter is presented by Rachner et al. (2002). The trajectory of liquid jets and liquid mass flux density in supersonic crossflows has been investigated by Yates (1972). However drop size distributions for liquid injection into supersonic crossflows have not been published yet. This is partially due to a lack of measurement techniques (Balasubramanyam et al., 2006). In all cases the mass flux ratio of gas to liquid is by far higher compared to quench setups where the liquid is actually cooling the hot gas by its evaporation. Referring to this supersonic quenching is also a novelty. Evaporation of droplets has been widely studied and a multitude of correlations have been proposed. Most common are the correlation for heat and mass transfer by Ranz and Marshall (1952), who determined drop evaporation up to temperatures of 220 °C. Drop evaporation at higher temperatures was investigated by Renksitzbulut (1991). A review on droplet evaporation models was recently published by Sazhin (2006). For spray calculation the model of Abramzon and Sirignano (1989) is widely used in practical applications. But nevertheless there are only few works on quench cooling of hot gas streams by evaporation of injected liquids (Siepmann and Gusewell, 2000). In these applications an excess of water is injected to increase the gas–liquid interface and cooling rates. Therefore the gas is leaving the quench saturated at the cooling limit temperature. These quench systems only deal with low gas velocities and do not consider or take advantage of gasdynamic cooling effects. Thus the supersonic quenching system is a completely new application. It utilizes the high gasdynamic cooling rates, which cannot be reached by direct or indirect cooling devices, and reduces afterwards the total enthalpy of the gas stream by the total evaporation of injected liquids.

2. Supersonic quench design

2.1. Gasdynamic cooling

In the convergent divergent laval nozzle the static gas temperature is decreasing due to the proceeding acceleration of the gas. In the case of an adiabatic horizontal nozzle and a perfect gas the first law of thermodynamics results in a distinct relation between gas velocity w and static temperature T, whereas w_0 is zero and thus T_0 is the total temperature

$$0 = c_p(T - T_0) + \tfrac{1}{2}w^2 \tag{1}$$

At the nozzle throat the flow reaches the sonic speed w_s and a Mach number Ma of one, which are defined as follows:

$$Ma = \frac{w}{w_s} \quad \text{with} \quad w_s = \sqrt{\frac{\kappa p}{\rho}} = \sqrt{\kappa R T} \tag{2}$$

Therefore supersonic flows have a Mach number greater than one and equivalent subsonic flows a Mach number lower than one. Assuming isentropic flow conditions temperature, pressure as well as density at any position within the nozzle relate to the total conditions at the inlet. The respective ratios only depend on the local Mach number and the isentropic exponent κ:

$$\frac{T_0}{T} = 1 + \frac{\kappa - 1}{2} Ma^2 \tag{3}$$

$$\frac{p_0}{p} = \left(1 + \frac{\kappa - 1}{2} Ma^2\right)^{\kappa/(\kappa-1)} \tag{4}$$

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\kappa - 1}{2} Ma^2\right)^{1/(\kappa-1)} \tag{5}$$

In the case of a known Mach number progression it is possible to evaluate the flow conditions within the laval nozzle. Based on the continuity equation a one-dimensional area-Mach number relation can be developed for a perfect gas

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{Ma^2}\left(\frac{2}{\kappa+1}\left(1 + \frac{\kappa - 1}{2} Ma^2\right)\right)^{(\kappa+1)/(\kappa-1)} \tag{6}$$

The Mach number at any position is directly related to the nozzle throat area A*, whereby the equation always has a supersonic and a subsonic solution. Based on these equations one can estimate the flow conditions within the laval nozzle to compare different nozzle configurations. To illustrate the gasdynamic cooling within the supersonic quenching system Mach number, pressure and static temperature profiles are presented in Fig. 1. The utilized geometry already corresponds to the later presented

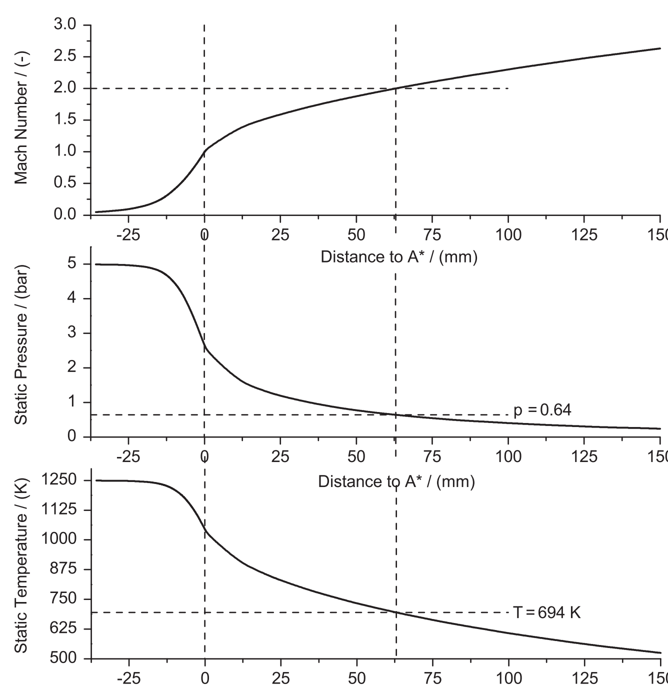

Fig. 1. Characteristic isentropic laval nozzle flow without water injection.