Multiphase Spray Cooling Technology in Industry

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1. Introduction

Cooling by air-assisted water sprays has received much attention in the last decade because of the benefits it has shown over conventional cooling by methods such as forced air jets or single-fluid nozzles. Air-assisted water sprays are currently being used in many industrial applications. Some of these applications require rapid cooling from high temperatures, such as the cooling of medium thick plates and thin strips in the hot rolling steel mill, glass tempering in the auto industry, and electronic chip cooling in the computer manufacturing industry. Sprays dispersing fine droplets size referred to as air-mist sprays have been proposed for use in heat exchanger devices where the performance of heat exchangers can be tremendously improved by the injection of a small amount of mist with the forced air flow. The application of air-mist sprays has also found its way into the food processing industry in the cooling of vegetable produce on grocery shelves and chilling of beef and lamb carcasses at meat packing facilities. The purpose of this chapter is to present some of the basic principles for understanding multiphase sprays and to demonstrate their use. Since many aspects of multiphase sprays can be discussed, this chapter focuses mainly on the flow dynamics and the heat transfer associated with multiphase cooling. Several industrial applications are presented. These include: quenching of upward and downward facing heated plates by air-assisted water sprays, the use of air-mist sprays in heat exchangers, and chilling of vegetable produce and processed meat by air-mist sprays. The discussion will provide an insight into the optimal flow conditions for best heat transfer effectiveness and best spray coverage. Several factors that influence the spray cooling effectiveness and droplets impaction will be introduced including the spray droplet size, water flow rate, air-to-liquid loading, and nozzle-to-surface distance.

2. Flow Dynamics in Multiphase Sprays

Air-assisted sprays consist of a mixture of air and liquid. An air stream of high velocity accelerates the liquid droplets. The nozzles contain two flow chambers: a pressurized liquid chamber and a pressurized air chamber (Figure 1). The discharging liquid and air streams collide towards the nozzle center. The pressurized air surrounds and impinges on the liquid flowing from the nozzle orifice and atomizes the liquid film. There are several factors that affect droplet size, such as the spray pressure, and air-to-liquid loading. Smaller droplet sizes in the spray can be generated by either increasing the air pressure while decreasing the liquid pressure, or by increasing the airflow rate while decreasing the liquid flow rate. An increase in the pressure difference between the liquid and air results in an increase in the relative velocity between them. This leads to an increase in the shear force acting on the liquid, which produces finer droplets. A similar effect occurs by increasing the air-to-liquid loading. Figure 2 shows the air stream-lines and droplets flow for a typical spray application. Circulation regions are shown to develop downstream of the flow towards the target surface and away from the stagnation point.

Depending on the flow operating conditions, air-assisted spray atomizers are able to generate a spectrum of droplets sizes that can range from few microns (referred to as fine mist) to several millimeters in diameter. The nozzle system consists of an air actuated nozzle body assembly and a spray setup fixture consisting of an air cap and a fluid cap. Simply by changing the air and fluid caps, sprays with different drop size spectrums can be generated. As the droplets exit the nozzle, their trajectories are influenced by several factors such as: droplet size, droplet impinging velocity, ambient temperature, relative humidity, nozzle-to-surface distance, and wind speed and direction (if applicable).

The spray droplet size has a strong influence on the spray heat transfer (Issa & Yao, 2004 & 2005). The smaller the droplet size, the easier it is for the droplet to evaporate at the surface; thus leading to higher heat transfer effectiveness. However, smaller size droplets may never reach the target surface but instead will cool the thermal boundary layer near the surface by increasing the near surface local evaporation. On the other hand, large size droplets can have a detrimental effect on the surface cooling because of the flooding that may occur at the surface. Droplets with higher impinging velocities tend to spread more at the surface (Chandra & Avedisian, 1991). The more the droplets spread at the surface the higher is the heat transfer effectiveness. In certain applications where the surface is heated to temperatures beyond the Leidenfrost point, a vapor layer will develop quickly at the surface. Droplets with low impinging velocities may not be able to penetrate through this film layer. However, for higher impinging velocities droplets can penetrate through the film layer, and more surface contact can be established. An increase in the nozzle-to-surface distance will lead to a decrease in the droplet impinging velocity (also a decrease in droplet momentum) at the surface. This is due to the longer duration the drag force will be acting on the droplet. With less momentum, the droplets surface impaction efficiency will decrease. Surface and ambient temperatures and relative humidity also have an affect on the droplets impaction (Issa, 2008-b). The evaporation rate of the droplets increases with the increase in the surface or ambient temperature. This results in smaller size droplets developing while the droplets are airborne. This also leads to more droplets drifting away and reduces the impaction efficiency. A similar effect takes place when Low relative humidity levels are present. Finally, wind speed and its direction (as in the case of agricultural sprays) have a strong influence on the spray drift (Lawson & Uk, 1979). By increasing the droplets size or the injection velocity, spray drift will reduce. During the last decade, electrostatic charging of the droplets (Zheng et al., 2002) has also been introduced as a means for reducing the spray drift and enhancing the penetration and deposition of the droplets onto the target surface (canopy plants). Spray drift will reduce because the droplets trajectories will then be influenced by the electrostatic forces as they try to follow the electric field lines.

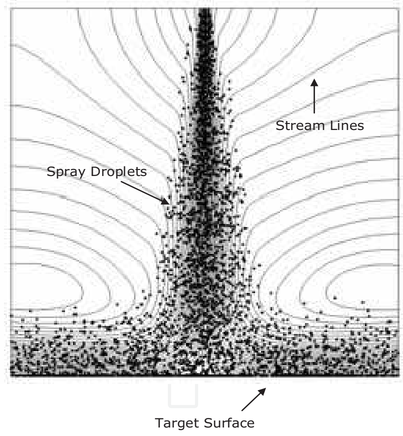


Fig. 1. Air-mist spray nozzle Fig. 2. Typical simulation for spray flow over a target surface

In order to maximize the spray cooling effectiveness over the target surface, it is important to reduce the amount of drift by maximizing the droplets surface impaction. The spray impaction efficiency, η, is defined as the ratio of the actual droplets mass flow flux deposited onto the target surface, G, to the maximum droplets mass flow flux leaving the nozzle, G_{max}:

$$\eta = \frac{G}{G_{max}} \tag{1}$$

Sprays with large droplets have high impaction efficiency unlike sprays with small size droplets which have difficulty staying the course of their initial trajectory and simply drift along the air stream as they approach the target surface. The orientation of the surface with respect to the spray affects the spray impaction efficiency. For example, it is expected that the impaction efficiency on a downward-facing surface to be much lower than that on an upward facing surface due to the effect of gravity pulling on the droplets downwards (refer to Figure 3).

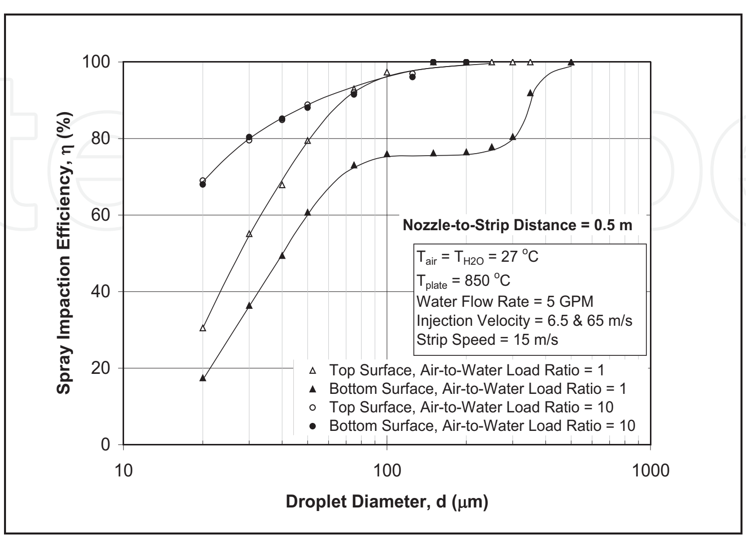


Fig. 3. Droplet impaction versus droplet diameter

When spray droplets make it to the surface, there are three possible ways they can interact with the surface: stick, rebound or breakup at the surface. A droplet will stick to the surface when it approaches the surface with low incoming momentum (i.e., low incoming velocity or fine droplet size). Upon impaction, the droplet will adhere to the surface in a nearly spherical form. With an increase in the droplet incoming momentum, a droplet will rebound at the surface. During impaction, the droplet will spread radially in the form of a flattened disk. After the droplet reaches maximum spread, it will begin to recoil backwards towards its center as it leaves the surface due to the surface tension effect. The droplet spread at the surface is function of the droplet deformation on impaction, which is a process of energy transformation between kinetic and surface energies. The understanding of the droplet bouncing behavior at surfaces near room temperature (Scheller & Bousfield, 1995; Mundo et al., 1997) and at metallic surfaces heated above the Leidenfrost point (Wachters & Westerling 1966; Karl et al., 1996) is well established for sprays dispersing water droplets. For metallic surfaces heated to temperatures above the Leidenfrost point, the droplet coefficient of restitution (ratio of outgoing to incoming droplet velocity) at the surface is shown to be dependent on the impinging droplet Weber number (ratio of droplet inertial force to surface tension force). As the droplet incoming momentum increases beyond a critical value, the droplet will disintegrate during impaction at the surface. It has been found that the number of produced satellite droplets will increase with the increase in the incoming droplet momentum (Issa & Yao, 2004).

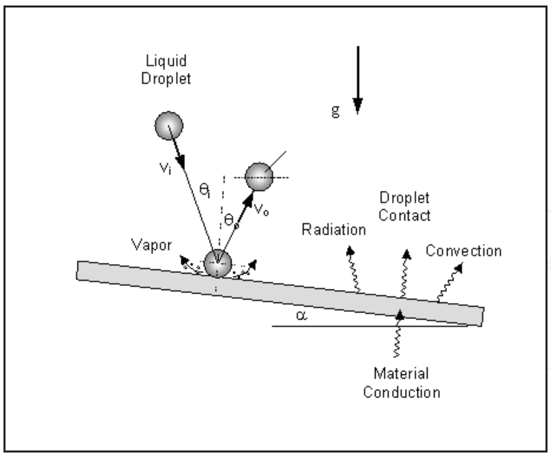
Figure 4 shows the interaction of a droplet with a heated surface. After impacting the surface, the droplet changes its speed and trajectory. This can be quantitatively measured by the normal and tangential coefficient of restitution. Data gathered from several sources for water droplet impactions at atmospheric conditions and on surfaces heated to temperatures above the Leidenfrost point (Hatta et al., 1997; Karl et al., 1996; Wachters & Westerling, 1966; and Naber & Farell, 1993) show the relationship between the droplet normal coefficient of restitution, e_n, and the normal impinging droplet Weber number, We_n, (Figure 5) to be as follows:

$$\mathbf{e_n = 1 - 0.1630 We_n^{0.3913}} \qquad (2)$$

Where,

$$\mathbf{We_n = \frac{\rho_d v_{i,n}^2 d}{\sigma_d}} \qquad (3)$$

ρ_d is the droplet density, $v_{i,n}$ is the droplet impinging normal velocity at the surface, d is the droplet diameter and σ_d is the droplet surface tension. Experiments performed by Karl et al. (1996) on surfaces heated above the Leidenfrost temperature show the loss in the droplet tangential momentum to the wall to be about 5%. Recent models for fuel spray-wall impingement in diesel engines have assumed a fixed value of 0.71 for the tangential coefficient of restitution (Lee & Ryou, 2000).



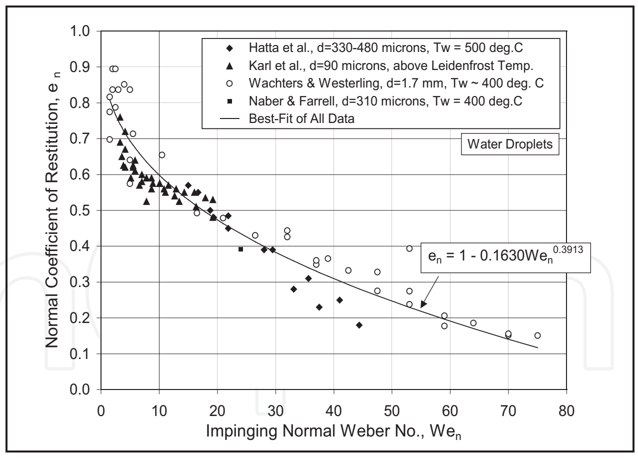


Fig. 4. Droplet bounce at the heated wall

Fig. 5. Droplet normal coefficient of restitution at steel plates heated above the Leidenfrost temperature

3. Heat Transfer in Multiphase Sprays

Air-assisted water sprays are used in the cooling of high or low temperature surfaces in many industrial applications. Applications associated with rapid cooling from high temperatures include thin strip casting, glass tempering and electronic chip cooling, while low temperature cooling applications include beef or lamb carcass chilling, and chilling of food and vegetable produce.

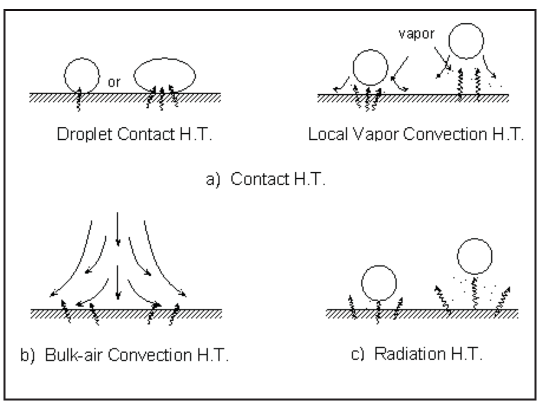
3.1 Quenching of metallic surfaces heated above the saturation temperature

For metallic surfaces heated to temperatures above the droplet saturation temperature, there are three modes of heat transfer associated with the multiphase spray cooling process (Figure 6). These are: a) conduction and convection associated with the droplet contact with the heated surface, b) convection associated with the bulk air flow and the droplet cooling of the thermal boundary layer, and c) surface radiation. For sufficiently high incoming droplet momentum, better droplet-to-surface contact and therefore better surface wetting can be established if surface flooding and droplet-to-droplet interactions are minimized. Those two effects are detrimental to cooling.

When surfaces are heated to the critical heat flux (nucleate boiling), spray heat transfer is referred to as heat transfer by wet contact. This is due to the fact that the droplets are in continuous or semi-continuous contact with the heated surface. In this case, the surface heat transfer is at its maximum. When surfaces are heated to the Leidenfrost temperature, spray heat transfer is referred to as heat transfer by non-wet contact. This corresponds to the case where after a short period of droplets contact with the surface, a film layer is generated quickly between the droplets and the surface preventing further direct contact. The heat transfer in this case is at its minimum. In this latter cooling regime, the incoming droplets momentum have significant influence on the cooling efficiency. For sufficiently high incoming momentum, the droplets can penetrate through the film layer, and more surface contact can be established leading to higher spray cooling effectiveness.

A comparison between the two boiling regimes (wet and non-wet cooling) is shown in

Figure 7. Sprays can always be characterized as either dilute sprays, intermediate dense sprays, or dense sprays. The deciding parameter is the flow flux (water mass flow rate per unit surface area). Spray flow fluxes less than 2 $kg/s.m^2$ are considered to be dilute sprays (Deb & Yao, 1989), while flow fluxes slightly above 2 $kg/s.m^2$ are associated with intermediate dense sprays. For both boiling regimes, the higher the impinging droplet Weber number the stronger is the droplet contact heat transfer. This should not be confused with the spray Weber number which is different. At a certain critical droplet Weber number (Figure 7), the droplet will disintegrate during impaction at the surface. For dilute sprays, the droplet contact heat transfer is expected to increase linearly with the impinging droplet Weber number because droplets interaction is minimal. As the droplet size increases, the spray transitions from dilute to intermediate dense to dense spray. As a result, surface flooding and droplet-to-droplet interactions also increase. This leads to saturation in the droplet contact heat transfer (refer to actual curves in Figure 7).



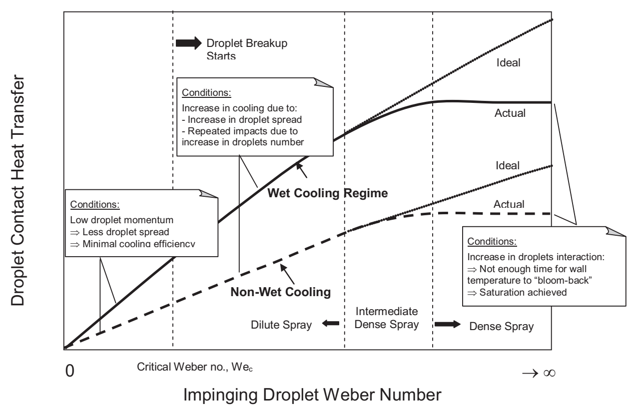


Fig. 6. Spray heat transfer modes for surfaces heated above saturation temperature
Fig. 7. Droplet contact heat transfer

For high temperature surfaces, the maximum release of heat from the spray consists of: a) the pre-boiling cooling potential of the liquid droplets, b) the release of heat when the liquid droplets completely evaporate at the surface, and c) the superheating of the vapor to the surface temperature. The spray heat transfer effectiveness, ε, is expressed as:

$$\varepsilon = \frac{q''}{G\left[h_{fg} + c_{p,l}(T_{sat} - T_l) + c_{p,v}(T_s - T_{sat})\right]} \quad (4)$$

where, $\mathbf{q''}$ is the droplet heat flux, G is the water mass flux (defined as the water mass flow rate per unit surface area), h_{fg} is the enthalpy of vaporization, $c_{p,l}$ is the liquid specific heat constant, $c_{p,v}$ is the vapor specific heat constant, T_{sat} is the liquid saturation temperature, T_l is the liquid temperature, and T_s is the target surface temperature.

Researchers have experimented with two types of nozzles: single-phase fluid nozzles that disperse water alone, and multiphase-fluid nozzles that disperse water and air. Auman et al. (1967), Fujimoto et al. (1997), and Ciofalo et al. (1999) have conducted experiments using nozzles that disperse water droplets alone, while Ohkubo and Nishio (1992), Toda (1972), Puschmann and Specht (2004) have used nozzles dispersing water droplets with air. Sozbir and Yao (2004) have conducted experiments using both water, and water with air. All of these experiments were conducted on plates heated to temperatures above the Leidenfrost point. Experimental data gathered from the above sources is compiled and presented in Figure 8 which shows the spray heat transfer effectiveness as function of the spray Weber number. Results reveal multiphase sprays to be more efficient than single-phase sprays. This is because air injected with water increases the droplets momentum and enhances the impaction and heat transfer. The spray Weber number in Figure 8, We_s, is defined as follows:

$$We_s = \frac{G^2 d}{\rho_d \sigma_d} \quad (5)$$

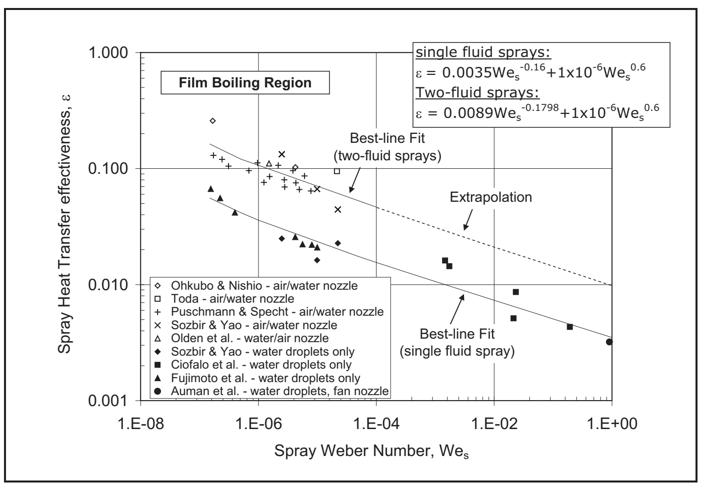


Fig. 8. Spray heat transfer effectiveness for single fluid and two-fluid nozzles

During impaction, the droplet mass can be recalculated based on the droplet contact heat transfer empirical correlation (eqn. 4), and the excess mass that is the difference between the incoming droplet mass and the re-calculated mass (after the droplet makes contact) is released as saturated vapor near the surface. The released vapor mass has the same momentum and energy of the liquid phase from which it was created. The released vapor mass, m_v, can be calculated from the droplet enthalpy change before and after impaction as shown in the following equation (Issa, 2003):

$$m_v = \frac{(\varepsilon\text{-}1) m_d c_{p,1} (T_{sat} - T_d) + \varepsilon m_d + h_{fg} + \varepsilon m_d c_{p,v} (T_s - T_{sat})}{c_{p,v} (T_s - T_{sat}) + h_{fg}} \quad (6)$$

where in the above equation m_d is the droplet mass before impaction.

3.2 Chilling of non-metallic surfaces heated to near room temperature

There are three modes of heat transfer associated with the air-mist chilling of surfaces heated to temperatures slightly above room temperature. These are: a) convection heat transfer associated with the bulk air flow, b) evaporation heat transfer of the droplets while airborne and at the surface, and c) sensible heat transfer associated with the droplets contact with the surface. The total heat transfer rate, q_{total} , can be expressed as:

$$q_{total}=h_a A(T_s-T_\infty)+m_e h_{fg}+m_w c_{p,1}(T_s-T_\infty) \quad (7)$$

Where h_a is the bulk air heat transfer coefficient, A is the chilled surface area, T_∞ is the air temperature, m_e is the droplet evaporation mass flow rate, and m_w is the mass flow rate of the impinging droplets. In this low surface temperature cooling regime, the spray heat transfer enhancement factor, ξ, can be defined as the ratio of the heat transfer of the two-phase flow (i.e., air and liquid water), q_{total}, to the heat transfer of the single-phase flow (i.e., air alone), q_a :

$$\xi = \frac{q_{total}}{q_a} \quad (8)$$

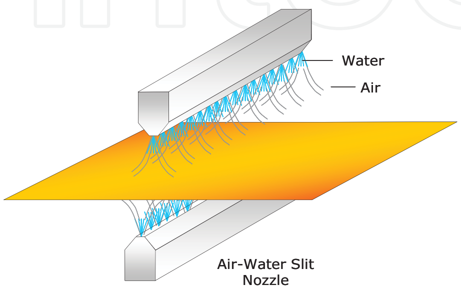
For low temperature applications, in order to reduce the amount of water loss from dehydration by the product during cooling (as in the case of processed meat and vegetable chilling), it is important to maximize droplets impaction to create a thin water film layer on the target surface. The water film layer will allow some of the water to penetrate through the surface pores to minimize the amount of water loss due to dehydration. Optimizing both the droplets surface wetting and the heat transfer is essential in these applications. There is an optimal droplet size that is best suited to achieve both maximum heat transfer and surface wetting capability.

4. Multiphase Sprays in Industrial Applications

4.1 Spray quenching of thin metallic strips

In thin strip casting, glass tempering, and electronic chip cooling, air-assisted water spray cooling (Figure 9) promises to be the most efficient method for cooling due to the increase in the surface contact area between the liquid droplets and the hot surface. Cooling by air-assisted water sprays has its advantages. It provides uniformity in cooling that leads to improvement in the material properties (glass and steel strips) and flatness control of the finished product (steel strips). It is also cost effective because it optimizes the amount of water consumption, and reduces the expenses associated with water recycling and filtration. Studies have been recently conducted on upward-facing (Issa & Yao, 2004, 2005) (Figure 10) and downward facing surfaces (Issa, 2007) (Figures 11 and 12) to model the transportation process of the spray, droplets impaction, and heat transfer phenomena. Parametric studies were conducted to investigate the effect of the droplet size, air-to-liquid loading, nozzle-to-surface distance and flow operating conditions on the droplets impaction and heat transfer enhancement.

Gravity is shown to have a strong effect on the spray impaction. As the air flow rate increases while keeping the water flow rate the same, the spray impaction efficiency on the top and bottom surfaces becomes almost identical (Figure 3). Spray impaction enhances as the air loading increases due to the increase in the droplet momentum. Spray impaction is also strongly dependent on the droplet size, and increases as the droplet size increases. Large droplets result in high terminal velocity and make it to the surface, while it is possible for small droplets to completely evaporate before reaching the target surface. In the cooling of a downward-facing surface, the droplet net incoming momentum and gravitational force act in opposite directions. Therefore, it is possible that for a certain spray droplets size the gravitational force may overcome the net flow momentum and cause the droplets to fall backward before hitting the surface. From the heat transfer side, the smaller the droplet size, the better is the spray heat transfer effectiveness. However, for a downward-facing surface there is an optimal droplet size that is best suited for optimizing both the spray impaction and heat transfer. The selection of this optimal droplet size depends on the flow operating conditions and the nozzle-to-surface distance.



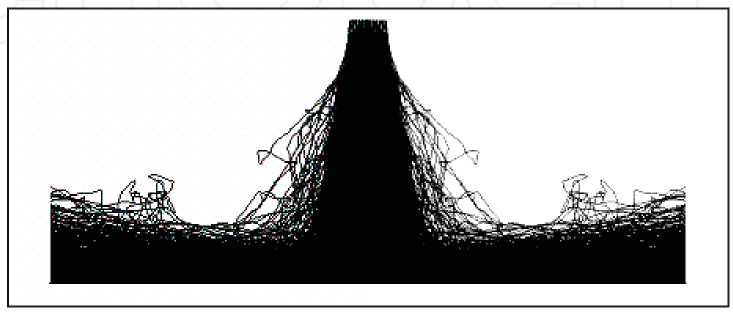
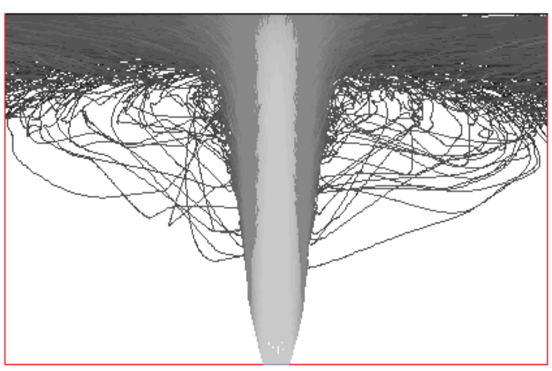


Fig. 9. Water-air spraying system
Fig. 10. Spray simulation for 20 μm droplets (spraying from top)



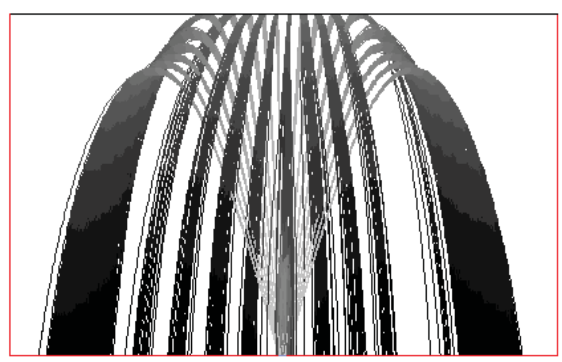
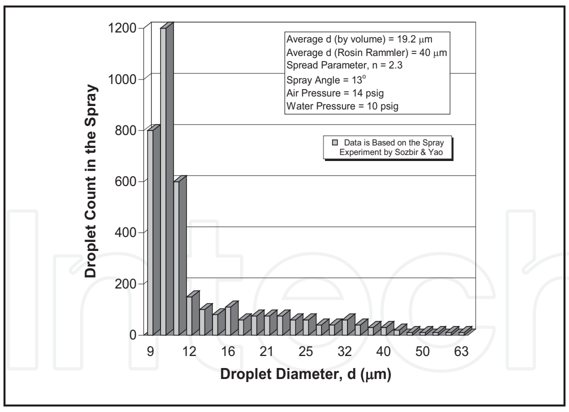


Fig. 11. Spray simulation for 100 μm droplets (spraying from below)
Fig. 12. Spray simulation for 1000 μm droplets (spraying from below)

In air-assisted water sprays, a wide range of droplets sizes can be generated during atomization based on the flow conditions of the water and air flows. Typical results are shown in Figure 13 (Issa & Yao, 2005). In this case a full conical spray type is injected from a distance of 40 mm above a stainless steel plate heated to 525°C. The air and water mass flow rates are $2x10^{-3}$ and 10^{-4} kg/s (20:1 loading ratio), respectively. The nozzle spray angle is 13°, and the air velocity is 35 m/s. Based on these conditions, the two-phase fluid nozzle disperses a spectrum of droplet diameters ranging from 9 to 63 μm with an average diameter of 19.2 μm by volume. A comparison between the modeling of spray heat transfer and experimental data for the air-water quenching of the heated plate is shown in Figure 14 (Issa & Yao, 2005). Using a multi-size spectrum for droplet distribution, droplets contact the wall at random locations with the largest hitting in the vicinity of the jet impingement point and the smaller droplets hitting further away, resulting in uniform cooling away from the plate center.



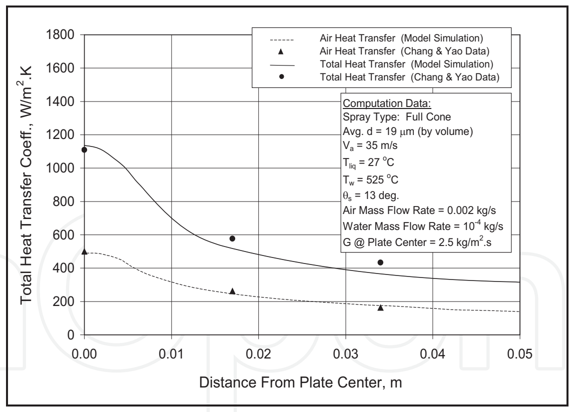


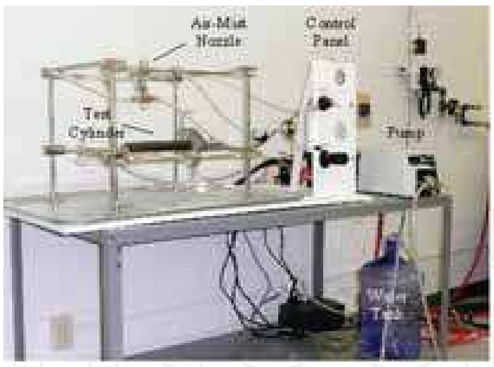
Fig. 13. Spectrum of water droplet distribution count

Fig. 14. Simulation versus experimental data for the air-water quenching of a steel plate (top surface)

4.2 Spray cooling in heat exchangers

In the external cooling of heat exchangers, forced air has been traditionally forced over the exterior surface of the heat exchanger. However, the usage of air alone reduces the overall efficiency of the system. As a result, further enhancement of the external cooling in a heat exchanger has been of critical concern. Experiments have been conducted for the external cooling of heated cylindrical surfaces where mist is being injected with forced air flow (Issa, 2008-a). Results show that with the introduction of mist with air, the overall heat transfer effectiveness can increase by up to 700%. The use of air-mist can result in a considerable reduction in the consumption of the forced air (therefore, reducing energy consumption) that is traditionally required to cool the exterior surface of the tubes in a shell-and-tube heat exchanger device.

Experimental and numerical simulation studies were recently conducted to investigate the effect of the spray operating conditions on the heat transfer enhancement in the cooling of cylindrical surfaces heated to temperatures in the nucleate boiling region. Test measurements show the dependency of the air-water spray heat transfer and droplets dynamics on factors such as the spray droplet size, liquid-to-air loading and water flow rate. Figure 15 shows the overall experimental system setup. Figure 16 shows a close-up view of the location of the drilled holes along the cylinder wall. The air-mist nozzle in this setup provided a spectrum of droplets ranging from 5 to 100 microns. The size of the water droplets produced is controlled by the nozzle operating flow conditions and the liquid-to-air loading ratio. Smaller size droplets are generated by increasing the air pressure while decreasing the liquid pressure, and vise versa.



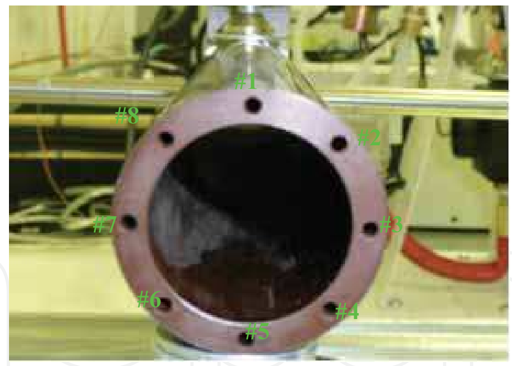
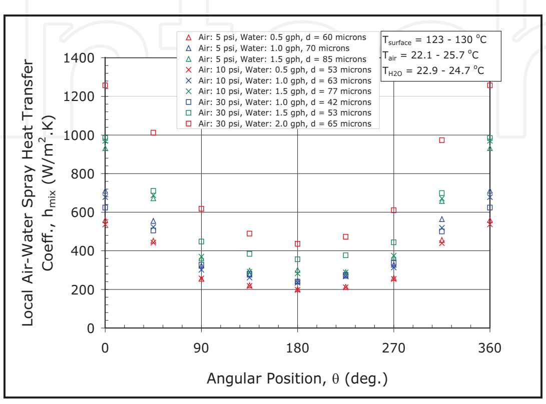


Fig. 15. System setup for spray cooling of a heated cylinder
Fig. 16. Arrangement of the drilled holes on a steel cylinder

The local air-water heat transfer coefficient is calculated for the eight angular positions on the cylinder surface, and the results are shown in Figure 17 (Issa, 2008-a). A comparison is made between the test cases where air and water are being dispersed. The results show the heat transfer coefficient to be highest at the stagnation point, and gradually decreases as the hydrodynamic boundary layer develops over the cylinder surface. As the water flow rate increases, the spray becomes denser and water flooding near the stagnation point is seen to increase. Figure 18 shows the spray average heat transfer coefficient as function of the water mass flow rate. The sharp increase in the heat transfer coefficient at high liquid loadings is due to the ballistic impaction of the spray which has a favorable effect on the enhancement of the heat transfer.

Results show for dilute sprays (water flow flux around 2 kg/s.m^2 or less), larger size droplets result in better cooling. However, for dense sprays, smaller size droplets result in better cooling. This is due to the fact that in dense sprays there is more interaction between droplets, and large size droplets will lead to an increase in surface flooding which is detrimental to the heat transfer. In dilute sprays (which have lower spray momentum than dense sprays), large size droplets increase the droplets incoming momentum causing the droplets to spread more at the surface during impaction, and therefore enhance the heat transfer. Experimental tests show that as the air pressure increases, the spray becomes ballistic, and therefore, causes a tremendous increase in the satellite droplets generated during impaction which enhances the heat transfer.



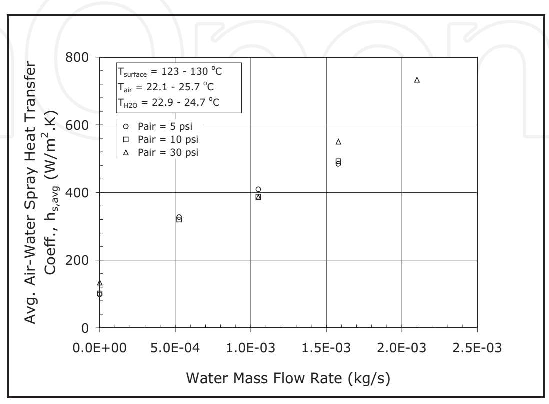


Fig. 17. Local air-water spray heat transfer coefficient versus angular position on the test cylinder
Fig. 18. Average value of the spray heat transfer coefficient over the cylinder surface versus water mass flow rate

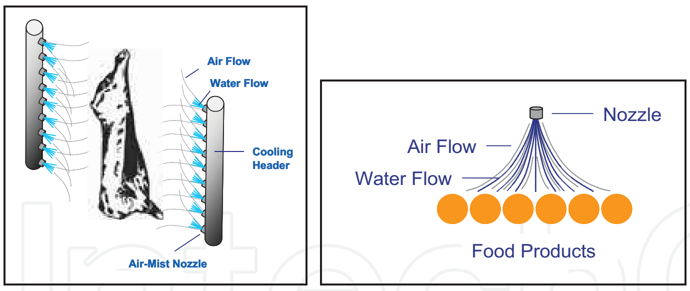
4.3 Spray chilling of food and meat products

In the research on beef carcass chilling (Figure 19-a), a variety of chilling techniques have been adopted during the last decade by researchers that range from using conventional air chilling systems (Mallikarjunan & Mittal, 1994) to air-assisted chilling systems with a variety of intermittent cooling schemes (Strydom & Buys, 1995). In these studies, the amount of water used to cool the beef carcass ranged from 3.5 to 7 gallons per carcass and for spray cooling periods from 10 to 17 hours. Most of these commercial spray chilling systems use nozzles producing large size droplets such as full jets nozzles (1140-4300 μm average droplet size) and hollow cone nozzles (360-3400 μm average droplet size).

Computer modeling and experimental studies have been recently conducted on the spray chilling of food products (Figure 19-b) and beef test specimens (Figure 20) to investigate the effect of using a two phase flow (air and water) with a fine spray droplets size in the chilling process (Issa, 2008-b). The conducted studies show promising results where substantial improvements are made in the heat transfer enhancement. Recent experimental tests were performed to investigate the effect of the spray droplet size and water flow rate on the spray heat transfer. Test data show that the application of excess water is detrimental to the cooling effectiveness on a beef surface, and maximum heat transfer occurs when the spray median droplets size is less than 40 μm (Figure 21). However, surface flooding increases with the increase in droplet size, and when using a large amount of water, the cooling effectiveness of the multiphase spray reduces to that of a forced air jet.

For the same amount of air and water mass flow rates, sprays with larger droplets have lower droplet number density but higher droplet momentum. More droplets make impaction at the target surface than when finer droplets are dispersed, and the number of drifting droplets decreases sharply. As the air-to-liquid loading increases (for the same amount of water flow rate and same water droplets size), the impaction efficiency drastically increases due to the increase in the droplets impinging velocity and momentum. The rate of evaporation is governed by the gradient of the vapor concentration between the droplet and the bulk air. When the ambient is saturated (i.e., relative humidity is 1), the impaction efficiency slightly increases because the droplet evaporation rate is lowered. In general, as the nozzle-to-surface distance increases, droplets evaporation increases and larger droplets are needed to achieve higher impaction efficiency.

One of the challenges in air mist chilling is to understand the effect of the droplet size on the heat transfer enhancement. Since in air-mist chilling the cooling medium is a two-phase flow, the first question to be addressed is what desirable droplet size is required for best heat transfer enhancement. Also, in order to reduce the amount of water loss from dehydration by the product during cooling (as in the case of beef carcass or vegetable cooling), it is important to maximize droplets impaction to create a thin water film on the target surface. The second question to be addressed is what desirable droplet size is best suited to achieve both maximum heat transfer and surface wetting capability. Recent studies show the optimal droplet size required for maximum impaction is different from that required for maximum heat transfer enhancement (Figure 22). To optimize both the heat transfer and surface wetting criteria, a multi-objective optimization methodology can be applied where the net optimal droplet size is between the droplets median size required for maximum heat transfer and that required for maximum surface impaction.



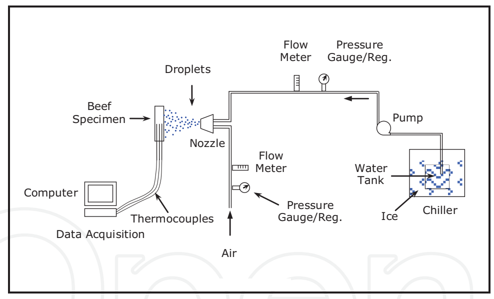
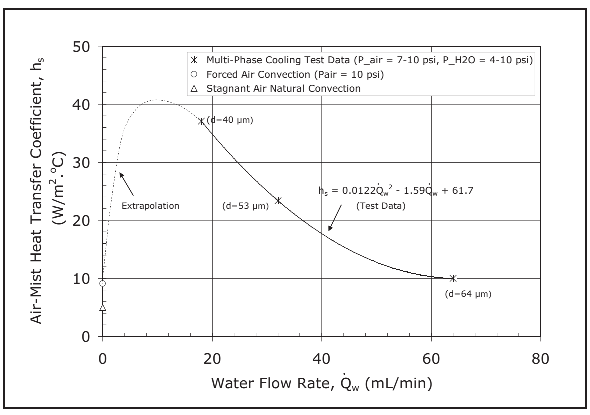


Fig. 19. Air-mist chilling: (a) beef carcass, (b) food products

Fig. 20. Experimental setup for chilling of beef test specimen



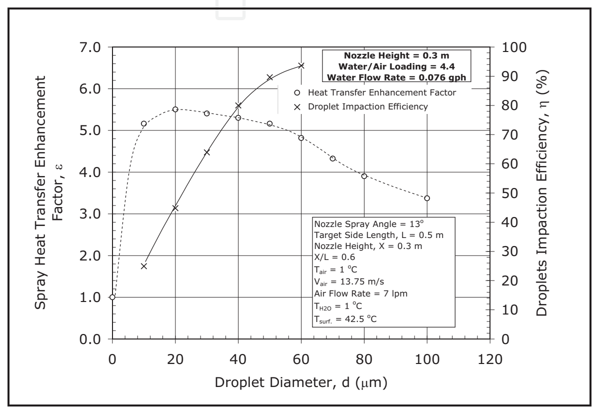


Fig. 21. Air-mist spray heat transfer coefficient versus water flow rate for the chilling of beef versus droplet diameter

Fig. 22. Heat transfer and impaction efficiency test specimen

High water mass flow flux has a detrimental effect on the surface cooling because of the flooding that can occur on the surface. Furthermore, if the spray droplets are too large, there is a risk of water running fast down the chilled surface. In the air-mist chilling of beef carcasses, water runoff on the surface has a detrimental effect on the quality of the processed beef because of the bleached streaks that can be produced on the surface. Therefore, predicting the amount of water flooding on the surface is very critical in the cooling operation. In the air-mist chilling of beef carcasses, water sprays are intermittently turned ON. As time elapses while the spraying system is ON, more water droplets accumulate on the surface, where on a vertical surface (as in the case of beef carcass), gravity acts on pulling the water-film downward. When the height of the water-film reaches a critical thickness, gravity overcomes the effect of surface tension and water starts running down the surface. The question of how fast the water-film runs down the surface depends on the size of droplets used in the spray. The droplet size plays a role in the time it takes the water-film to reach maximum speed during runoff. This information provides a clue to what the intermittent spraying time, and the frequency of spraying should be in the chilling operation. The amount of time required to reach a steady dripping velocity considerably decreases from about 30 s for the 20 μm droplets to 7 s for the 100 μm droplets. In order to avoid excessive water overflow, the spraying time should be substantially reduced when large droplets are sprayed.

5. Conclusion

Experimental studies and numerical simulations have been conducted on the use of multiphase sprays for cooling applications such as metal plate quenching, external cooling of heated tubes in exchangers, and chilling of food and meat products. Studies reveal the impaction efficiency and the heat transfer effectiveness of the multiphase sprays to be strongly dependent on the spray droplet size, air-to-liquid loading, and nozzle distance from the target surface. The impaction efficiency increases as the droplet incoming momentum increases such as by using sprays dispersing large size droplets. In certain applications where spraying is done in a direction opposite to gravity, the gravitational force may cause larger size droplets to fall backward before hitting the surface if the spray momentum is not sufficiently strong. On the heat transfer aspect, the smaller the droplet size, the better is the spray heat transfer effectiveness. However, in all cooling applications, there is an optimal droplet size that is best suited for optimizing both the spray impaction and heat transfer effectiveness.

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This book, edited by the Intech committee, combines several hotly debated topics in science, engineering, medicine, information technology, environment, economics and management, and provides a scholarly contribution to its further development. In view of the topical importance of, and the great emphasis placed by the emerging needs of the changing world, it was decided to have this special book publication comprise thirty six chapters which focus on multi-disciplinary and inter-disciplinary topics. The inter-disciplinary works were limited in their capacity so a more coherent and constructive alternative was needed. Our expectation is that this book will help fill this gap because it has crossed the disciplinary divide to incorporate contributions from scientists and other specialists. The Intech committee hopes that its book chapters, journal articles, and other activities will help increase knowledge across disciplines and around the world. To that end the committee invites readers to contribute ideas on how best this objective could be accomplished.