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ScienceDirect
Procedia Manufacturing 8 (2017) 754 – 760
Procedia MANUFACTURING

14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa

Investigation of the parameters governing the performance of jet impingement quick food freezing and cooling systems – a review

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Abstract

Jet Impingement Technology (JIT) is a heat transfer enhancement technique. Available literature soundly confirm its wide applications in the cooling of combustion chambers, critical parts of turbines, glass technology, electronic components, drying of paper and textile materials, drying of biomaterials and food preservation. The technology has interesting fluid dynamics and heat transfer properties. Its relative simplicity and low cost, abundance of air, generation of high heat transfer and faster freezing rates have made it a subject of extensive investigations. Several investigations on jet impingement quick food freezing and cooling systems which range from visualization, experimental, computational simulations and or numerical analysis, factorial and mathematical models have been studied. This paper reviews the governing parameters of the jet impingement quick food freezing and cooling systems.

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing

Keywords: Jet impingement, food, freezing, cooling, parameters

1. Introduction

The early 1990s earmarked the introduction and engineering of the impingement freezer technology to the marketplace by Frigoscandia Equipment for a wide variety of thin food products [1]. From the report, this came as a result of continued research by food processors to develop technologies that could freeze food products faster for a

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Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing
doi:10.1016/j.promfg.2017.02.097

number of benefits. The benefits included keeping pace with newer high-speed formers and other high-speed production line equipment upgrades, providing better economic yields as a result of reduced freezing cost, and preserving the quality of the food products. Impingement freezing utilizes high velocity air jets that are directed perpendicular to the surface of the food [2]. High velocity air jets are reported to reduce thermal barriers surrounding the food product surface [3], increasing convective heat transfer coefficients and allowing for faster freezing of the food product sealing it in its freshness [4]. The time it takes to freeze food is a very important factor in the preservation of food [5, 6]. The main appeal of this technology is to increase the rate of heat transfer so as to reduce the freezing time of food as quickly as possible to maintain its safety and quality. Faster freezing is reported to result in smaller ice crystals which result in reduced cellular damage of the food products which will then be juicier, have better texture and exhibit less dehydration (drip loss) when thawed. The technology is widely used for preservation of sandwich egg patties, thin bakery products, chewing gums, sticky cookie dough, confectionery products, fish fillets, shrimp, potato products, meat patties, poultry parts and fillets. The system is said to be governed by many parameters which include, freezing air temperature and velocity [7], nozzle to food spacing or distance from the stagnation point, geometry of food slab, its dimensions, food product water content; specific heat for unfrozen and frozen food, thermal conductivity, food density and its initial and final target temperature, latent heat of fusion, conductivity of packing material, convective heat transfer coefficient [8, 9], Reynolds number [10, 11, 12], design of the injections, orientation of the impinging air to the target surface [13], type, size and shape of nozzles [14,15,16]. The current paper reviews these parameters and their effects on the performance of jet impingement quick food freezing systems.

Nomenclature

A	round jet area (m^2)
D	nozzle diameter or width (m)
h	convective heat transfer coefficient (W/m^2 K)
Nu	Nusselt number
H	nozzle-slab distance (m)
V	air jet velocity (m/s)
Re	Reynolds number
S	slot nozzle area (m^2)
R	radial distance (m)
L	nozzle length (m)
H/D	nozzle-plate distance to jet diameter ratio
L/D	nozzle length to jet diameter ratio

2. Jet impingement quick food freezing or cooling parameters

The impinging jet flow patterns can be categorised into three characteristic regions namely, the free jet region, impingement or stagnation flow region and wall jet region [7]. The free jet region was further classified into three sub-regions namely, the potential core region, developing flow region, and developed flow region. Maximum heat transfer between the flow and the surface was reported to be experienced in the stagnation region. The slowest cooling zones (SCZs) are found to lie off-centre in the wall jet region. Figure 1 shows the schematic diagram of a typical flow structure of an impinging jet on an object surface. Impingement process produces high but also spatially variable convective heat transfer coefficients due to the variations of flow patterns in the jet impingement regions [6]. Variation of heat transfer on the food surface is a point of interest when using air impingement freezing or cooling systems. This was reported to cause undesirable variations in certain quality attributes on the food product as a result of localized hot and cold spots on the food product surface. This has been a useful indication for the need to optimize impingement system heat transfer on the entire food surface, a subject that has brought extensive studies of the parameters that govern the performance of impingement quick food freezing or cooling systems. A review of some of the studies conducted on impingement food freezing or cooling parameters is presented in this section.

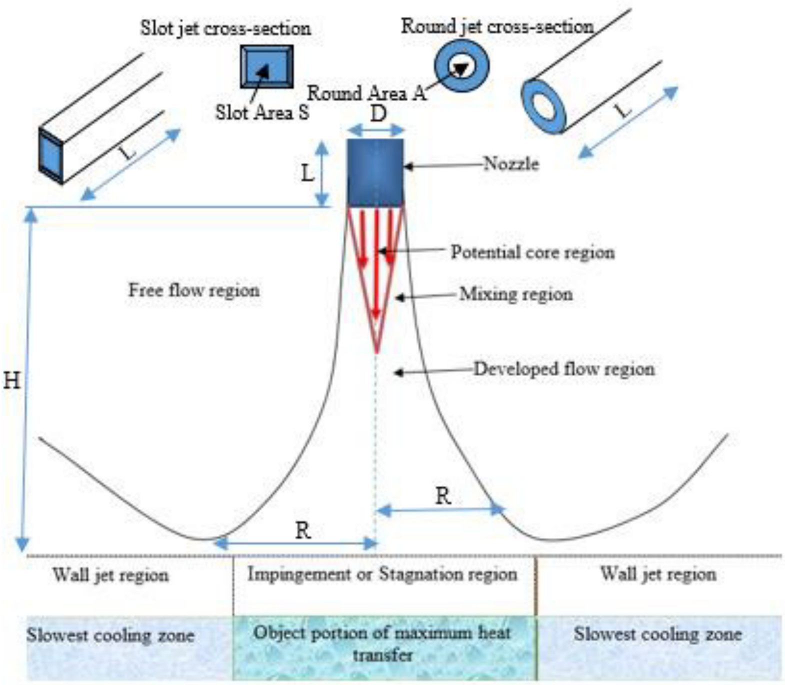

Figure 1. Schematic diagram of the typical flow structure of an impinging jet on an object surface [2]

Salvadori and Mascheroni [3] analysed the performance of impingement freezers by studying the heat and mass transfer that occur during the impingement freezing process. According to the authors, high heat transfer coefficients of around 400 W/m^2 K at high velocities of 40 m/s gave a marked reduction in processing times which increased economic benefits as a result of reduced weight losses. The authors found that impingement technology was valid for removing unbound water and cited excessive internal diffusion as a potential cause of product degradation. Impingement freezing was said to be effective for freezing thin products while in thicker products, excess of surface dehydration was reported to cause product injury. The authors further pointed out that nozzle configuration and the number of nozzles directed onto the food surface affect the rate of heat transfer. Jet configurations where air was exited through orifices in the impingement surface when exit orifices were not aligned with entrance orifices were found to have the highest h values (20 – 30% higher). They recommended the use of multiple arrays of nozzles from both the top and bottom of the food product to enhance heat transfer. Food product shape was found to be another limitation of the impingement performance. It was further reported that the shape of the nozzle is an important parameter for impingement performance as they have great influence on air flow and consequently on the heat transfer coefficients. The high velocities of heat and mass transfer reported in the impact or stagnation regions were found to enhance high heat transfer coefficients. The influence of nozzle configuration in obtaining optimum Nusselt number (Nu), finding H =5.55 and S = 0.2H as optimum values were also discussed. H represented nozzle-slab distance to the nozzle diameter relation (dimensionless) and S being the slot nozzle area. The authors also reported the high data experimental analysis of the effect of radial distance R (radial distance/jet diameter) measured from the stagnation point and the distance between jet and plate H (nozzle-plate distance/jet diameter), both dimensionless parameters. The results obtained showed that Nu is a function of Re, H and R. Nu was found to decrease with R in the zone near to the stagnation point and was a maximum in the stagnation point for H above 2 where the h-values were also found to be a maximum.

Kaale et al [4] studied the super-chilling of food. The authors discovered that ice content and the percentage of the water in a product that is in solid form are important parameters of food when freezing is involved. They recommended temperature control to stable levels prior and during storage treatment to avoid significant levels of ice crystal growth that can cause food tissue damage. High air velocities were noted to produce maximum heat transfer coefficients which resulted in reduced impingement freezing and cooling times. The use of nozzle configuration which impinges on both the top and bottom surfaces of the food product was reported to play a key role in reducing processing times and therefore yield quality frozen food products with extended shelf life.

Jafari and Alavi [5] numerically studied food freezing by slot jet impingement using Computational Fluid Dynamics (CFD) to predict the effects of various parameters on the freezing time of a food slab. The results showed that the freezing air temperature and velocity as well as the nozzle to food spacing distance affect the freezing time of the food slab. The parameters that were studied include shape, dimensions, water content and specific heat of unfrozen and frozen, thermal conductivity, density, initial and final temperature of the food, latent heat of fusion, conductivity of packaging material, convective heat transfer coefficient, initial freezing temperature and freezing medium temperature which are all correlated and are not easy to get an exact analytical solution due to nonlinearity of moving boundary conditions. These were solved using CFD. High heat transfer coefficients were again found in the stagnation region. Lower air temperatures and higher air velocities resulted in reduced freezing times and same happened to mass flow with sublimation but these changed slowly beyond the critical point. The h-values were found to increase with increase in velocity. It was also found that, when the nozzle to food distance decreased, the nozzle jet was confined and freezing time increased and vice versa. However, further increase of the impinging distance was found to reduce fluid momentum needed to drive the forced convection and consequently increased the thermal barrier. The authors suggested a nozzle-to-food distance ratio of 6-8 to avoid excessive energy dissipation.

In their studies on mathematical modelling of air-impingement cooling of finite slab shaped objects and effect of spatial variation of heat transfer coefficients, Erdogdu et al [6] discovered that the increase of heat transfer coefficient (h-value) plays a pivotal role in reducing the impingement freezing or cooling time of food products. This in turn was reported to be achievable at higher air velocities. Rapid cooling was further reported to prevent micro-organism growth thereby increasing food safety, improving its quality, preventing overcooking and destruction of nutrients with the potential of reducing evaporative weight losses. The authors used the lumped system analysis to evaluate the spatial variation of the h-values over the surface at air nozzle exit velocities (v) of 14 and 28 m/s which yielded maximum h-values of 71.6 and 101.7 W/m^2 K respectively in the stagnation region. In this study, the authors did not investigate the effects of air velocity on the product quality since they did not use a model food system. They recommended further studies to be carried out to find out the highest velocity that may be used to prevent the quality changes using real food model systems.

Sarkar and Singh [7] visually studied the effects of nozzle exit velocity, nozzle design, boundary layer characteristics on the surface of the product and the design of the impingement equipment on the performance of impingement freezing using planar flow visualization techniques as in Figure 2. The studies were conducted for various nozzle diameters (D), lengths (L) and nozzle to plate spacing (H) for flow over flat surfaces and food products with single and double jets using transition features, recirculation, confinement and boundary layer flow characteristics. As in the studies conducted by Jafari and Alavi [5] the authors used the ideal range for the characteristic non-dimensional ratio (H/D) in the range of 6–8. It was visually observed that single free jets showed that the longer nozzles (larger L/D ratios) had a narrower spread which resulted in less viscous dissipation in the free jet regions. It was also visualised that small manufacturing defects (surface roughness) and minor nozzle internal constrictions had the potential of deflecting flow from the jets for long nozzles resulting in uneven flow patterns. Longer jets were also reported to be more difficult to clean which promotes blockage and is unhygienic in food applications. The visualisation studies confirmed and thus concluded that for food processing applications, H/D should be maintained in the range of 6–8 as reported in literature. Shorter H/D ratios were found to cause confinement, which resulted in disturbance to the main jet streams.

In their numerical study of steady and unsteady flow and heat transfer from a confined slot jet impinging on a constant heat flux wall, Lawal et al [11] made the following findings:

- Height-to-width ratio and jet inlet velocity have significant influence on the flow and heat transfer characteristics of jet impingement on the flat plate
- Larger domain sizes generated greater heat transfer rate and flow instabilities

- Higher jet inlet velocity led to unsteady flow, and enhanced high heat transfer rates on the target plates

In the study of air impingement cooling of boiled eggs, Erdogdu et al [12], h-values and heat fluxes higher than those of the traditional systems were observed in the stagnation region. This was found to markedly speed up to the cooling process of the boiled eggs. The use of lower temperature air was also found to reduce the cooling time. The results obtained showed no significant difference between the cooling time of the traditional water immersion and air impinging. However, air impingement would have the advantage of eliminating the waste water and cross-contamination associated with water immersion. The H/D ratio of 3 was found to be an optimum value for cooling cylindrical shaped products. The authors further suggested that for industrial use, the use of jets from top and bottom of the product or an impingement tunnel where the eggs are rolling might improve the cooling time.

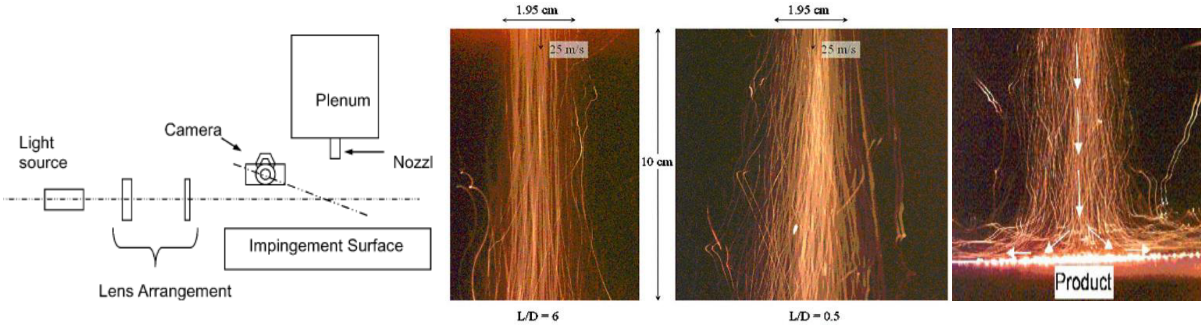

Figure 2. Schematic setup for flow visualization and flow visualization images [7]

Yang et al [13] experimentally studied the effects of nozzle configuration and curvature slot jet impingement cooling on concave surface. The studies also focused on the effect of nozzle shape as they considered round shaped nozzle, rectangular shaped nozzle and 2-D contoured nozzle. The experiments were conducted by varying the nozzle exit Re and nozzle to surface distance under constant heat flux condition to determine the corresponding h-values. The results obtained were reported to show the influence of the nozzle shapes on heat transfer generated. The slot jet or rectangular nozzle was found to offer the highest turbulence intensity and high Nu and h-values in the stagnation and free jet regions than round shaped and 2-D contoured nozzles. Results for 2-D and round nozzles were similar due to the similarity of the edge shape at the nozzle exit. Heat transfer was found to be more enhanced on concave surfaces than on flat plates due to curvature effects.

3. Summary

JIT was introduced in the early 1990s. The technology utilizes high velocity air jets that are directed perpendicular to the food surface. The impingement jet can be categorised into three regions, namely the free jet region, impingement or stagnation flow region and wall jet region. Maximum convective heat transfer coefficients are generated in the stagnation region. The system is capable of generating very high convective heat transfer coefficients and is widely used for various industrial applications. However, the high convective heat transfer coefficients generated by the impingement process are spatially variable due to the variations of flow patterns in the jet impingement regions and this calls for the need to study and optimize the many process parameters that govern the system. Freezing time is of great importance to the safety and quality of the frozen food product. Faster freezing times have been found to promote good food quality of prolonged shelf life. Multiple arrays of nozzles from both the top and bottom of the food product were found to enhance heat transfer. The slot jet (rectangular) nozzles were found to offer the best turbulence intensities which generate high convective heat transfer coefficients. High velocities were noted to result in high Re and Nu values and reduced freezing times. Temperature control is very important in impingement freezing to avoid food tissue damage. A nozzle-to-food distance ratio of 6-8 was visually, experimentally and numerically confirmed and recommended to avoid excessive energy dissipation. Small manufacturing defects (surface roughness) and minor nozzle internal constrictions were visualised to have the potential of deflecting flow from the jets for long nozzles resulting in uneven flow patterns. Longer jets were reported to be more difficult to clean which promotes blockages and tend to be unhygienic when used in food applications. Shorter H/D ratios were found to cause confinement, which resulted in disturbance to the main jet streams and became weaker to break the thermal barriers surrounding the food product surface. Impingement freezing is cheaper due to abundance of air and hygienic unlike water immersion cooling which wastes water and suffers cross-contamination. Numerical analysis and CFD analysis play a very important role in predicting the optimum parameters of the impingement freezing and cooling systems.

4. Conclusion

The performance of impingement freezing and cooling is governed by many parameters. A number of studies that concentrated on the effects of the parameters on the technology have been reviewed. Most of the parameters are closely related and their combination is of equal importance and require careful design and optimization. Best optimized values have been achieved through visualization studies, numerical analysis and computational simulations. High air velocities were noted to yield high Re, Nu and h-values which resulted in high heat transfer rates and faster freezing rates that are key players in maintaining the safety and quality of food products in its prolonged shelf life. Slot jet nozzles produce higher heat transfer coefficients compared to round and 2-d contour nozzles. The close correlation of impingement parameters calls for high order numerical modeling for optimization of the parameters which are validated experimentally.

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