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Drying of moist food snacks with innovative slot jet reattachment nozzle

Farzad, M.[a*]**; Yang, M.**[a]**; Yagoobi, J.**[a]**; Tilley, B.**[b]
Center for Advanced Research in Drying (CARD)
[a] Department of Mechanical Engineering. Worcester Polytechnic Institute (WPI), Worcester, USA
[b] Department of Mathematical Sciences. Worcester Polytechnic Institute (WPI), Worcester, USA.

*E-mail of the corresponding author: mfarzad@wpi.edu

Abstract

Drying of moist porous media such as paper, pulp and food products is one of the most energy intensive processes in industry. Impinging jet nozzles are commonly used in various drying processes. There have been many efforts to improve the transport characteristics of impinging jet nozzles. Utilizing innovative Slot Jet Reattachment (SJR) nozzle is an approach to make the drying process more efficient. This is mainly because these nozzles overcome the high flow rate constraint associated with the traditional Slot Jet (SJ) nozzle.

In this paper, the drying characteristics of the SJR nozzle with exit angles of +20° and +45° are experimentally investigated. The samples used are snack cookies. The results are compared with those of SJ nozzle under the same mass flowrate. The results indicate that significant enhancements in drying rates are achievable with both SJR nozzles compared to SJ nozzle.

Keywords: *Drying; Porous Food Snack; Slot Jet Reattachment Nozzle; Slot Jet Nozzle*

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1. Introduction

Energy is one of the grand challenges for manufacturers in the 21st century. In traditional industrial processes, the energy required for drying can take up to 25% of the corresponding total energy use [1]. Energy efficient and uniform drying of food products such as fruits, chips, and cookies is of critical importance to the product quality. Slot Impinging Jet (SJ) nozzles are widely used to dry food in traditional food industry, providing the principal heat and mass transfer mechanism in the drying process. To design a proper impinging jet nozzle with sufficient efficiency, many factors need to be considered: nozzle geometry and size, nozzle configuration, nozzle-to-surface separation, jet-to-jet separation, cross flow, jet exit velocity and surface motion [2].

Among such various factors, an innovative Slot Jet Reattachment (SJR) nozzle, has been developed by Page and Seyed-Yagoobi [3] and Seyed-Yagoobi et al. [4]. Compared to the conventional SJ nozzle, the innovative SJR nozzle can alter the direction of impinging air flow to an outward radial direction, with a flow reattaching on a ring away from the centerline, where the stagnation point occurs (see Fig. 1). Heat and mass transfer is maximized along the reattachment ring. Due to the nature of turbulent viscous mixing along the boundary layers of the impinging air, a secondary flow is introduced through mass entrainment, which means part of the air steam directs inward radially to form a circulation region underneath the bottom plate of the nozzle. A relatively low-pressure distribution is maintained. The intense turbulent flow is the principal reason for the high mass and heat transfer rate. These flow characteristics of the SJR nozzles provides significant advantages over the conventional SJ nozzles. By using SJR nozzles, the average heat transfer over the surface as well as local heat transfer rate can be greatly enhanced, and a controllable exerted force minimizes the mechanical impact to fragile food products.

2. SJR Nozzle

SJR nozzle is a modified version of SJ nozzle. The schematic of SJR nozzle with exit angle of 45° is shown in Fig. 1 [5]. This innovative nozzle can be fabricated in different exit angles. Based on the application, exit angle can be toward the surface (positive angle) and outward the surface (negative angle). Explicitly, net force exerted on the impingement surface can be controlled by the exit angle of the nozzle. The flow exits the nozzle in two directions, First is in direction of minor axis which is in oval shape and second is in direction of major axis which is radial [4] [5] (Fig. 2).

In SJ nozzle, stagnation point is right under the center line and maximum heat transfer happens at the center of impingement surface but in SJR nozzle reattachment point is observed in an oval shape away from the center line of the nozzle. Therefore, reattachment area in SJR nozzle covers a larger space than that of SJ nozzle and moves outward and inward direction which leads to a higher average heat and mass transfer coefficient.

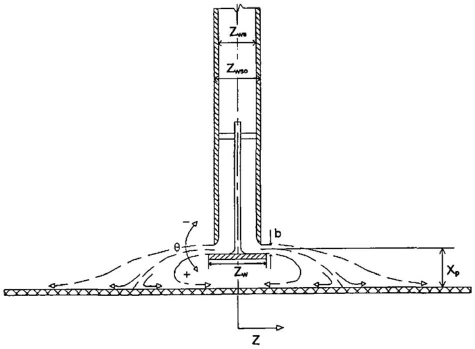

Fig. 2 Schematic of SJR nozzle

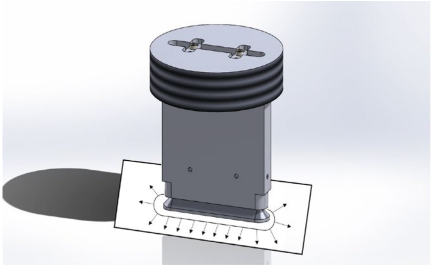

Fig. 1 Flow direction on impingement surface under SJR nozzle

In this study, all the tests were conducted with twoSJR nozzles with exit angles of +20˚ and +45˚. The geometrical parameters of these nozzles and SJ nozzle are listed in Table 1.

Table 1. Geometrical parameters of SJ and SJR nozzles

Parameters (mm)	**SJ Nozzle**	**SJR 20˚**	**SJR 45˚**
L	73	73	73
b	-	4	4
X_p	80	14	16
Z_w	-	18	14
Z_{ws}	9.25	10	9.25

3. Experimental Set Up and Procedure

The experiments were conducted at the optimum distance between the exit opening of nozzle and the impingement surface. Drying test with SJ nozzle was run based on optimal height of nozzle to surface spacing of 80 mm [4]. X_p for SJR+20˚ and SJR+45˚ was fixed at 14 mm and 16 mm, respectively, to accommodate for swelling of the samples during the early stage of drying [5]. In this paper, the samples used are raw cookie doughs. Each experiment consisted of two cookies. The drying characteristics with SJR and SJ nozzles are experimentally obtained and compared to illustrate the resultant enhancements in drying rates with the use of SJR nozzle. The comparisons are made under identical air mass flowrates.

The schematic of the apparatus used for this study is shown in Fig. 3. Air was conducted to the apparatus through 0.5 in diameter plastic hose from an upstream air supply. A threaded on/off valve was used to control the air mass flowrate. A rotameter was utilized to measure the air mass flow rate. For heating the air, an 8.5 kW torch electrical heater was utilized which was connected to a PID unit controller to regulate the power required to reach the desired temperature. Following the electrical heater, a solenoid valve activated with a timer was used to redirect the incoming air away from the sample during the sample weight recording. Threaded nozzle was connected interchangeably to the solenoid valve. A scale with an accuracy of 0.001 g was used to capture the sample weight during the drying process. Adjustable stand was used to hold the digital scale and adjust the distance between the nozzle and impingement surface. J-type thermocouples were used to measure the temperatures in different locations such as at the exit of electrical heater, nozzles exit, and impingement surface. Surface pressure was measured by a pressure transducer. The apparatus was well insulated to minimize the heat loss to ambient.

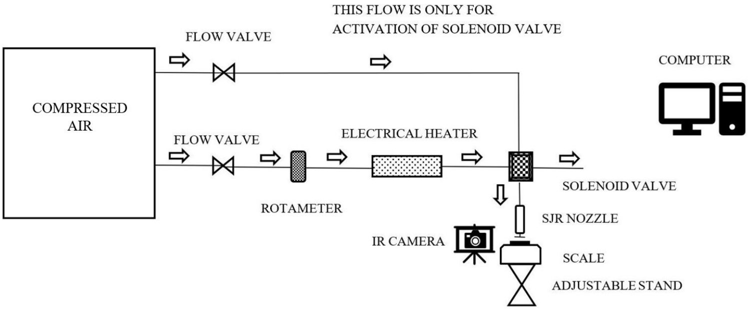

Fig. 3 Simplified schematic of apparatus used for this study

4. Experimental Results

All the tests were conducted under the same air exit temperature of 260 ˚C and two different mass flow rates. Operating conditions for mass flowrates of 0.005 kg/s (i.e. case 1) and 0.01 kg/s (i.e. case 2) are listed in Table 2 and Table 3.

Table 2. Operating conditions for case 1

	SJ Nozzle	**SJR 20°**	**SJR 45°**
b/Z_w	-	0.22	0.22
Re	6134	3875	4613
$\dot{m}$ (kg/s)	0.005	0.005	0.005
V (m/s)	6.19	7.34	8.74
$V_{s/c}$ (m/s)	6.19	6.19	6.19
T (˚C)	260	260	260

Table 3. Operating conditions for case 2

	SJ Nozzle	**SJR 20°**	**SJR 45°**
b/Z_w	-	0.22	0.22
Re	12269	7750	9226
$\dot{m}$ (kg/s)	0.01	0.01	0.01
V (m/s)	12.38	14.69	17.48
$V_{c/s}$ (m/s)	12.38	12.38	12.38
T (˚C)	260	260	260

Figure 4 shows the percent dry basis moisture content (DBMC) as a function of drying time. The corresponding operating conditions are shown in Table 2. The results indicate that the drying times to reach a specific DBMC with SJR nozzles are much shorter than those of SJ nozzle. For example, it took 31 minutes with SJ nozzle to reach a 10 percent DBMC level while with SJR+20˚ and SJR+45˚ the DBMC of 10 percent was reached in 18 and 15 minutes, respectively, corresponding to 42 and 52 percent decrease in drying time. To reach a lower DBMC of 4.5 percent, the SJ, SJR+20°, and SJR45° required 76, 40, and 38 minutes, respectively, corresponding to 47 and 50 percent reduction in drying times. Figure 4 also shows that the performance of the two SJR nozzles are almost similar with air flowrate of 0.005 kg/s.

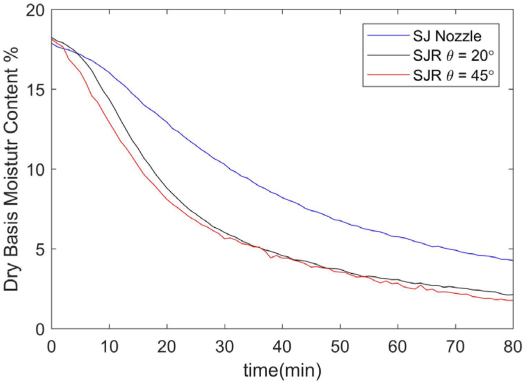

Fig. 4 Dry basis moisture content with air flowrate of 0.005 kg/s

Figure 5 shows similar results to those of Fig. 4 but under a higher air mass flowrate of 0.01 kg/s. The corresponding operating conditions for Fig. 5 are listed in Table 3. According to Fig. 5, the drying rates are higher with SJR nozzles compared to SJ nozzle at this higher air flowrate as well. However, the percent enhancements are lower than those of lower air flowrate of 0.005 kg/s. This is expected because as the air flowrate increases the drying rate increases as well regardless of the type of nozzle used making it more difficult to enhance the drying rate with SJR nozzles. However, the main reason for the SJR nozzles superior performance compared to SJ nozzle performance under the same exit air flowrate is mainly due to the differences in their flow fields. Specifically, the reattachment zone associated with an SJR nozzle is by far larger than the stagnation zone of the SJ nozzle resulting in a higher averaged heat transfer coefficient with SJR nozzles.

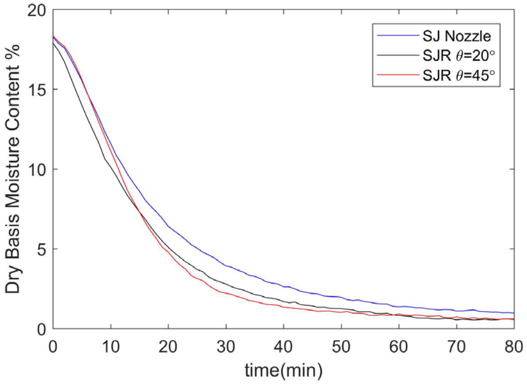

Fig. 5 Dry basis moisture content with air flowrate of 0.01 kg/s

Another appropriate way of evaluating the performance of three nozzles is to compare their drying rates as a function of percent DBMC as illustrated in Fig. 6. According to this figure, the drying rates of innovative nozzles are substantially higher than those of conventional nozzle over the whole range of sample moisture content. For instance, at DBMC of 15%, the drying rates for SJ, SJR+20˚, and SJR+45˚ nozzles are 0.07, 0.141, and 0.146 g/s, respectively.

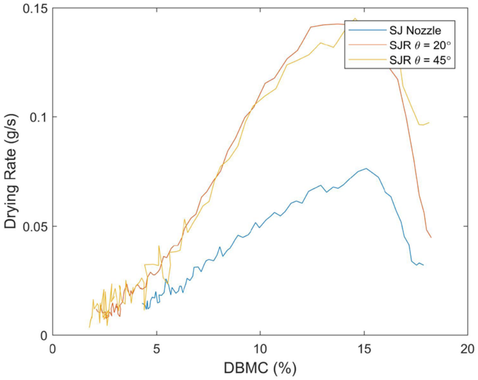

Fig. 6 Comparison of drying rate between SJ and SJR nozzles

To confirm repeatability of the data, drying experiments with SJR+20˚ under the mass flowrate of 0.01 kg/s and temperature of 260˚C were carried out three times. The minimum and maximum percent standard deviations of dry basis moisture content were 0.04 and 1.52. Additionally, the same repeatability tests were performed for SJ nozzle under the same operating conditions. The minimum and maximum percent standard deviations of dry basis moisture content were 0.05 and 0.92.

5. Conclusions

The convective air drying characteristics of two SJR nozzles with exit angles of +20° and +45° were compared to a conventional impinging SJ nozzle drying characteristics. The results confirmed that both SJR nozzles provide superior drying performance compared to that of SJ nozzle under the equivalent air mass flowrate. SJR nozzles are especially suitable for drying applications where it is crucial to protect fragile samples from being damaged by direct airflow impingement.

6. Acknowledgement

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7. Nomenclature

b	Exit width of the SJR nozzle	mm
D_h	Cross sectional hydraulic diameter of SJ nozzle	mm
$D_{h,exit}$	Exit hydraulic diameter of SJR nozzle (2b)	mm
DBMC	Dry basis moisture content	
DR	Drying rate	g/s
$\dot{m}$	Mass flowrate	kg/s
Re	Reynolds number:	
	$Re_{SJ} = (V.D_h)/\nu$	
	$Re_{SJR} = (V.D_{h,exit})/\nu$	
SJR	Slot Jet Reattachment	
L	Length of nozzle	mm
T	Temperature	˚C
V	Exit velocity	m/s
$V_{s/c}$	Slot channel velocity	m/s
X_p	Distance between nozzle exit and impingement surface	mm
Z_{ws}	Inside width of slot jet	mm

	Z_w	Bottom plate width of SJR nozzle	Mm
Greek letters			
	θ	Exit angle of SJR nozzle	degrees

8. References

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