

# Drilling of Glass Sheets by Abrasive Jet Machining

A. El-Domiaty, H. M. Abd El-Hafez, and M. A. Shaker

**Abstract**—Drilling of glass sheets with different thicknesses have been carried out by Abrasive Jet Machining process (AJM) in order to determine its machinability under different controlling parameters of the AJM process. The present study has been introduced a mathematical model and the obtained results have been compared with that obtained from other models published earlier [1-6]. The experimental results of the present work are used to discuss the validity of the proposed model as well as the other models.

**Keywords**—Abrasive Jet Machining, Erosion rate, Glass, Mathematical model.

## I. INTRODUCTION

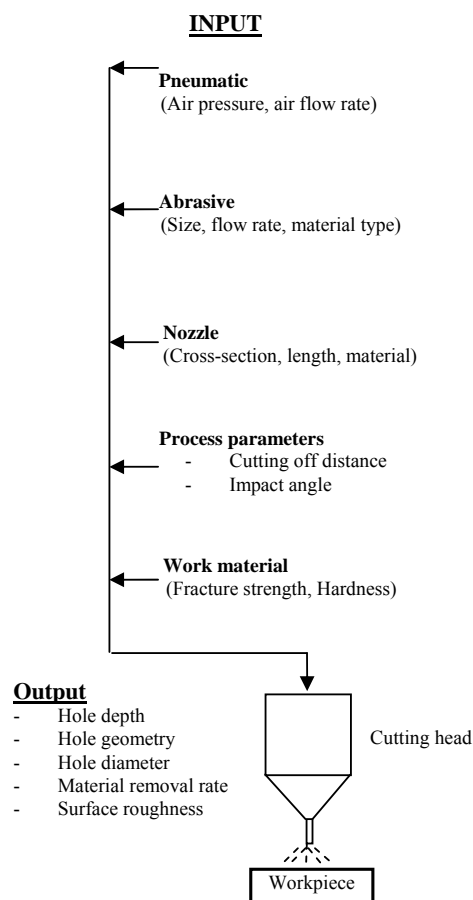
THE Abrasive Jet Machining (AJM) is considered as an attractive and effective machining method for hard and brittle materials [7-11]. Abrasive jet machining is similar to sand blasting process but in abrasive jet machining finer abrasive powders and smaller nozzles are used. Focusing on the abrasive jet stream from the nozzle onto the workpiece, smaller holes or slots can be machined on hard and brittle materials. Machining mechanism and characteristics of abrasive jet machining are major topics of many research works in the recent years [6-14]. The parameters associated with abrasive jet machining are summarized and shown in Fig. 1.

The abrasive size and the impact angle effects were studied by Wensink and Elwenspoek [10]. Their results showed that smaller abrasive size and less impact angle improve the machinability.

The nozzle pressure effect has been reported in many [15]-[19]. They proved that after threshold pressure, the Material Removal Rate (MRR) and the penetration rates have increased with increasing the nozzle flow pressure. Similarly, the effect of impingement angle has been reported and concluded that the maximum MRR for brittle material is obtained when normal impingement was applied.

Effect of abrasive grit size and mixing ratio, which is the ratio of the weight of the abrasive powder to the weight of the air and abrasive grits, has been thoroughly investigated by many researchers [20-22]. The stand-off-distance which is the

distance between the workpiece and the nozzle has also great effect on the material removal rate as well as the generated surface quality [14].



Micro-grooving of glass have been carried out by Park et al. [11]. The effects of workpiece properties as well as the process controlling parameters have been studied in many researches [13], [14], and [23]-[28]. Ghobeity *et al.* [29] had studied surface evolution models in abrasive jet micromachining and they found that the velocity decreased linearly from the centerline of the jet to the periphery, and that the probability of a particle arriving at the surface a given radial distance from the center of the impacting jet followed a Weibull distribution.

Well-established erosion models for brittle materials are

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reviewed [13] and the conclusions of the review show that the erosion rate ( $w$ ) is a function of the abrasive velocity ( $v$ ), the abrasive diameter (size) ( $d$ ), the abrasive density ( $\rho_a$ ), the workpiece toughness ( $K_{IC}$ ) and the workpiece hardness ( $H_f$ ). The validity of the erosion model has been established for a wide range of materials and abrasive particles [30]-[32].

Optimization of the process parameters of abrasive jet machining and other nontraditional processes have been found in Ref. [6]. Neelesh et. al. [6] have used the material removal model, produced by Sarkar and Pondy [16], in their analysis. The Neelesh's model is used in the present work to compare its prediction with the prediction obtained from the proposed model.

## II. EXPERIMENTAL WORK

Experiments were conducted to confirm the validity of the proposed model as well as the models found in the literature. The experimental work was carried on a test rig which was designed and manufactured in the workshops of the Faculty of Engineering, Port Said Egypt. The abrasive grits (sand) were mixed with air stream ahead of the nozzle and the abrasive flow rate was kept constant throughout the machining process. The jet nozzle was made of tool steel to carry high wear resistance. Several nozzles were manufactured with different bore diameters of 1 mm, 2 mm and 3 mm. Drilling of glass sheets was conducted by setting the test rig on the parameters listed in Table I.

TABLE I  
ABRASIVE JET MACHINING EXPERIMENTAL PARAMETERS

AJM Parameter	Condition
Type of abrasive	Sand ( $\text{SiO}_2$ )
Abrasive size	0.15-1.25 mm
Jet pressure	0.5 MPa (5 bars)
Cut-off distance	10 mm
Nozzle diameter	1, 2, 3 mm
Abrasive flow rate	3 g/min
Machining time	20 sec

The properties of abrasive (sand) and the workpiece (glass) are as follows;

Abrasive density	$= 2.3 \text{ g/cm}^3$
Glass hardness ( $H_v$ )	$= 30 \text{ GPa}$
Glass fracture toughness	$= 2.5 \text{ MPa } \sqrt{\text{m}}$
Glass stress flow ( $\sigma_{fw}$ )	$= 5000 \text{ MPa}$

## III. MODELING OF THE ABRASIVE JET MACHINING

In abrasive jet machining, the material removal takes place due to the impingement of the fine abrasive particles. These particles move with a high speed air stream. The abrasive particles are typically of 0.02 mm diameter and the air discharges at a pressure within a range of 2-8 bars.

When an abrasive particle impinges on the work surface at a high speed, the impact causes a tiny brittle fracture and the following air carries away the dislodged small workpiece

particle (wear particle). The impact of particles on the workpiece surface can cause severe erosion or material removal. The erosion process depends upon the number of abrasive particles striking the surface of the workpiece, their velocity and their direction relative to the surface of the workpiece. The mechanical properties of the workpiece are also major parameters controlling the erosion rate or the material removal rate.

Previous studies [3, 4, 33, 34] showed that the erosion rate (mass removed from the surface by unit mass of impinging particles) depends on the type of materials and the impact angles. These results are shown in Fig. 2. Ductile materials, such as mild steel, showed the greatest erosion rate at a shallow impact angle. On the other hand, more brittle materials such as glass and ceramics have rapid erosion rates when the particles were incident normal to the surface. The size of abrasive particles has also major effect on the erosion rate.

The results obtained by Sheldon and Finnie [34] showed that, on reducing the size of the silicon carbide particles from 127  $\mu\text{m}$  to 9  $\mu\text{m}$ , the erosion rate decreased and its maximum value occurred at an angle much lower, as shown in Fig. 3.

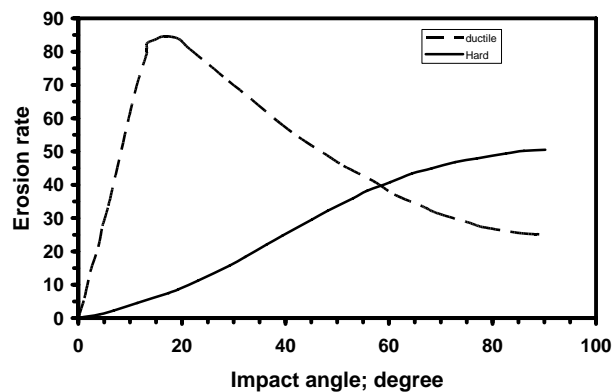


Fig. 1 Typical curves showing the variation of erosion with impact angle [33]

The principle factors affecting the erosion wear of brittle materials by solid particle impact are summarized in Table II.

The erosion rate  $V$ , which is defined as the eroded volume of target material to the volume of the impact particles, can be predicted by the aid of many relations, found in the literatures. Some of these relations and their references are given in Table III.

In order to introduce a mathematical model for the abrasive machining process, one of the equations given in Table III can be used as the building stone for that model since the mechanism of cutting is mainly erosion process.

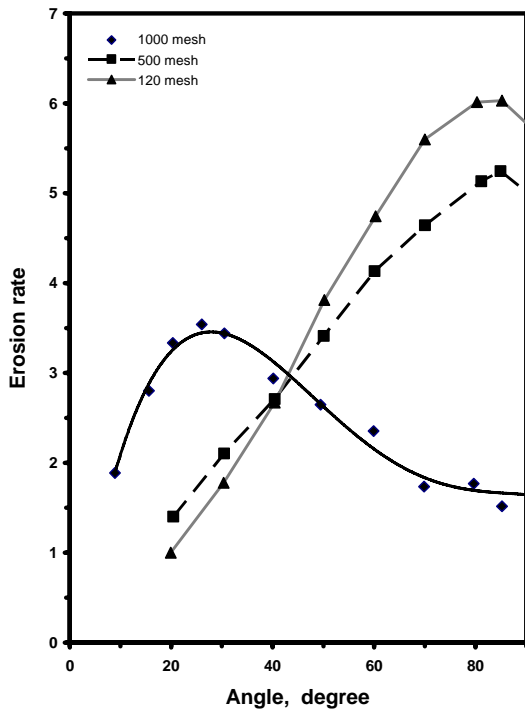


Fig. 2 Variation of erosion rate with impact angle for soda-lime glass eroded by silicon carbide particles with three different sizes [34]

TABLE II  
PRINCIPLE FACTORS AFFECTING THE EROSION WEAR OF BRITTLE  
MATERIALS BY SOLID PARTICLE IMPACT

Properties	Property	Symbol	Units
target material	Hardness	$H_t$	MPa
	Fracture toughness	$K_{Ct}$	MPa
			$\sqrt{m}$
impact particles	Hardness	$H_p$	GPa
	Fracture toughness	$K_{Ct}$	MPa
			$\sqrt{m}$
	Particle diameter	$d$	mm
Process parameters	Specific gravity	$\rho_a$	$g/cm^3$
	impact speed	$v$	m/s
	Impact angle	$\Theta$	degree
	Temperature	$T$	$^{\circ}C$

For convenience, equation (5) is used to estimate the volume removed from the target material per unit volume of the abrasive particle as the following;

$$V = \frac{C_1 v^{2.8} d^{3.9} \sigma_a^{1.4} H_t^{0.48}}{K_{ct}^{1.9}}; \quad g_{\text{material}}/g_{\text{abrasive}} \quad (7)$$

Multiplying the above equation by the flow rate of the mixture of abrasive particles and air ( $\dot{m}$ ), it is possible to obtain the material removal rate from the surface of the target material. The abrasive flow rate;

TABLE III  
SOME RELATIONS AND THEIR REFERENCES

Pub. Year	Ref. #	Relation	Eq. #
1976	1	$V \propto v^{2.5} d^4 \sigma_a^{0.25} H_t^{-0.25} K_{ct}^{-1.5}$	(1)
1978	2	$V \propto v^{3.166} d^{3.667} \sigma_a^{1.583} H_t^{-0.25} K_{ct}^{-1.333}$	(2)
1979	3	$V \propto v^{2.444} d^{0.333} \sigma_a^{1.222} H_t^{-0.111} K_{ct}^{-1.333}$	(3)
1982	4	$V \propto v^{2.333} d^{3.5} \sigma_a^{1.1667} H_t^{-1.41675} K_{ct}^{-1.0}$	(4)
1983	5	$V \propto v^{2.8} d^{3.9} \sigma_a^{1.4} H_t^{0.48} K_{ct}^{-1.9}$	(5)
2006	6	$\dot{m}_t \propto \eta_a \dot{m}_a v_a^{1.5} \sigma_{fw}^{-0.75} \rho_a^{-0.25}$	(6)

$$\dot{m}_a = \frac{\pi D^3 \rho_a}{4} \quad g_{\text{abrasive}}/s \quad (8)$$

The velocity of the abrasive particles, which are carried by air, can be determined by applying Bernoulli equation at two points. The first point is inside the nozzle and the second is outside the nozzle. With some assumptions and formula simplifications, the velocity can be obtained as follow;

$$v = \sqrt{\frac{2P}{\rho_{\text{air+abrasive}}}} \quad (9)$$

Assume that  $\rho_{\text{air+abrasive}} = \rho_a$ ; neglecting  $\rho_{\text{air}}$

Substituting (8) and (9) into (7) as follow;

$$\begin{aligned} \dot{m}_t &= \dot{m}_a V \quad g_{\text{material}}/s \\ \dot{m}_t &= \frac{C_1 v^{2.8} d^{3.9} \rho_a^{1.4} H_t^{0.48}}{K_{ct}^{1.9}} \dot{m}_a \\ \dot{m}_t &= \frac{C_1 v^{2.8} d^{3.9} \rho_a^{1.4} H_t^{0.48}}{K_{ct}^{1.9}} \cdot \frac{\pi}{4} D^2 v \rho_a \\ \dot{m}_t &= \frac{C_2 v^{3.8} d^{3.9} \rho_a^{2.4} H_t^{0.48} D^2}{K_{ct}^{1.9}} \\ \dot{m}_t &= \frac{C_3 P^{1.9} d^{3.9} \rho_a^{0.5} H_t^{0.48} D^2}{K_{ct}^{1.9}} \quad g_{\text{material}}/s \quad (10) \end{aligned}$$

Moreover, equation (6) which was established by Jain et. al. [3] for brittle materials was chosen to be compared with the obtained equation (10) as follows;

$$MRR = \dot{m}_t = \frac{K_3 \eta_a P^{1.25} D^2 \rho^{0.5}}{\sigma_{fw}^{0.75}}; \quad mm^3/s \quad (11)$$

This equation was obtained at the abrasive particles size ( $d$ ) range 0.01–0.15 mm. Substituting for  $m_a$  and  $v$  as in equations (8) and (9) into equation (11) gives;

$$m_t = \frac{K_2 \eta_a [D^2 \rho_a \{2P/\rho_a\}^{0.5}] \{2P/\rho_a\}^{0.75}}{\rho^{0.25} \sigma_{fw}^{0.75}} \quad (12)$$

To convert (12) to  $\text{g}/\text{s}$ ; (12) must be multiplied into the density of the abrasive material. Then, (13) could be obtained as follows;

$$m_t = \frac{K_3 \eta_a P^{1.25} D^2 \rho^{0.5}}{\sigma_{fw}^{0.75}}; g_{\text{material}} / s \quad (13)$$

#### IV. RESULTS AND DISCUSSION

##### A. Experimental Results

Fig. 4 shows the relationship between the cut-off distance and the required time to drill a glass plate with a 2 mm thickness. The results indicate that time decreased with increasing the cut-off distance up to 5 mm. The curve returns to higher time values above 5 mm distance. This is due to the abrasive stream has covered a wide area which decrease its effect on the spot. Moreover, the dimension of the required hole becomes not accurate as shown in Fig. 5. From these results, it can be concluded that the optimum cut-off distance is 5 mm under these conditions.

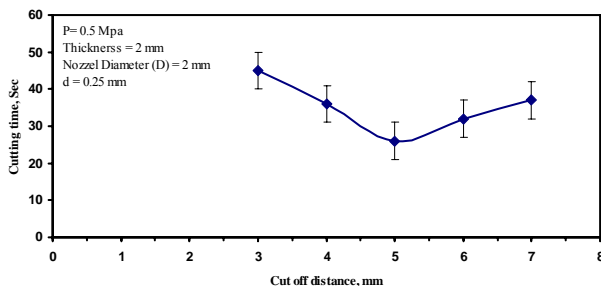


Fig. 3 Effect of cutting time on the cut-off distance using SiO abrasive particles

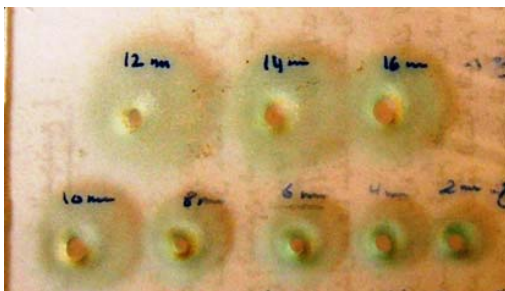


Fig. 4 A glass specimen drilled with the given data in Table I, at different cut-off distances

The effect of nozzle diameter ( $D$ ) on the material removal rate was studied at a pressure of 0.5 MPa and an abrasive size

( $d$ ) of 0.15 mm. The results were plotted in figure 6 with a standard deviation. The increase of the nozzle diameter increases the material removal rate due to the increase of the flow rate of the abrasive particles. Moreover, the increase of the abrasive size ( $d$ ) increases the material removal rate as shown in Fig. 7. The results indicate that the mass of the abrasive particles is an important factor in this machining process.

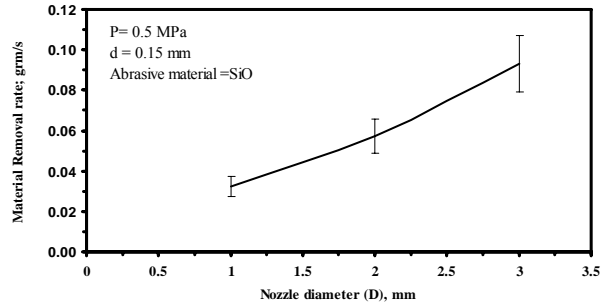


Fig. 5 Effect of nozzle diameter ( $D$ ) on the material removal rate of the glass

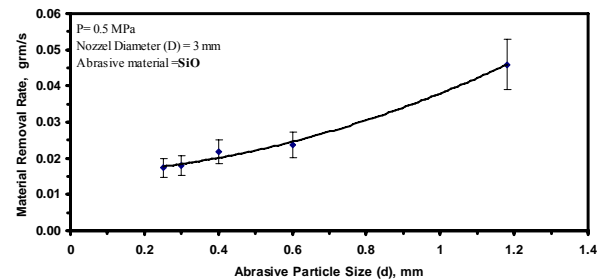


Fig. 6 Effect of abrasive particles size on material removal rate

##### B. Theoretical Results

From (10) it is possible to obtain some relationships between the material removal rate and both pressure and nozzle diameters at different particle sizes.

The pressure varied between 0.2 and 0.8 MPa; whereas, the particles diameters was in the range of 0.15-1.25 mm. These results are obtained at three different nozzle diameters of 1, 2 and 3 mm as shown in Figs. 5-7. The constant  $C_3$  is assumed to be unity and its value will be determined experimentally after comparing the experimental and the theoretical data.

The effect of nozzle diameter ( $D$ ) on the material removal rate (MRR), when different sizes of abrasive particles are used, is shown in Fig. 8. It shows that the nozzle diameter is an important factor affecting the MRR due to the resulted speed and flow rate of the abrasives. Therefore, large nozzle diameter causes material to be removed with higher values. The diameter of the abrasive material is also another key factor controlling the MRR. Lower sizes than 0.5 mm give very low values for MRR. Therefore, it is better to use larger abrasive sizes.

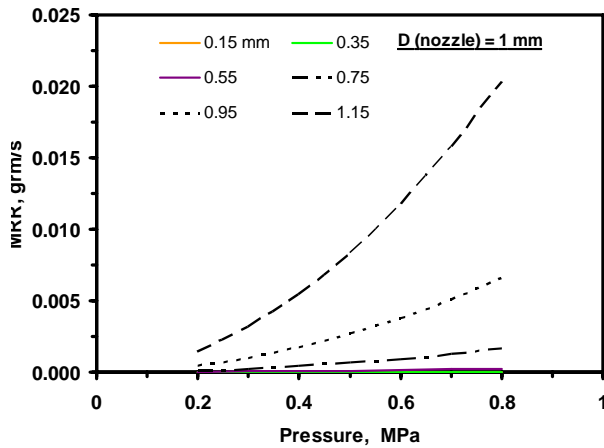


Fig. 7 Effect of pressure on the material removal rate at different size of abrasive particles for nozzle diameter of 1 mm

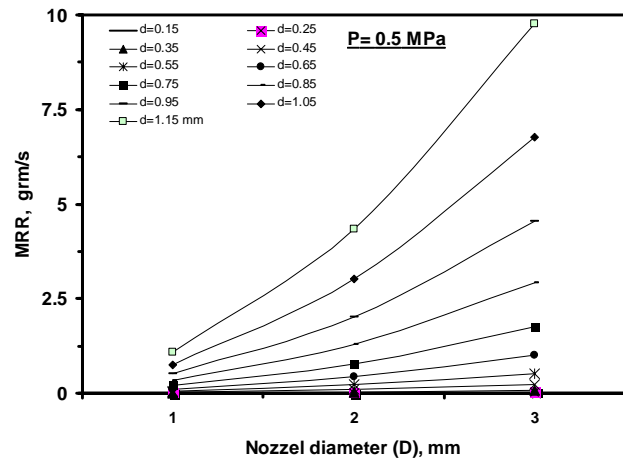


Fig. 11 Effect of nozzle diameter on the material removal rate at different size of abrasive particles carried out by model 1 (10)

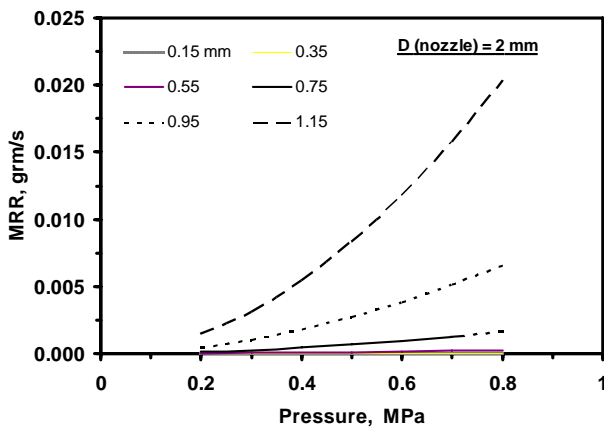


Fig. 9 Effect of pressure on the material removal rate at different size of abrasive particles for nozzle diameter of 2 mm

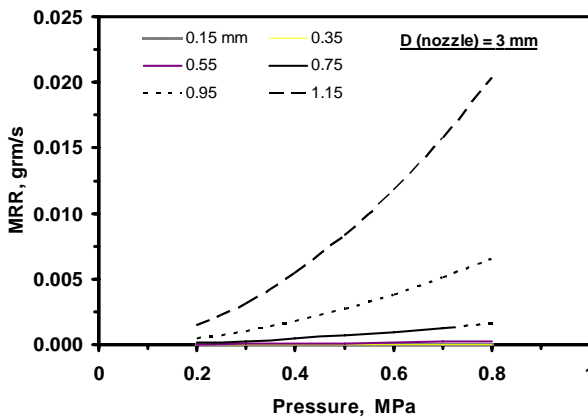


Fig. 10 Effect of pressure on the material removal rate at different size of abrasive particles for nozzle diameter of 3 mm

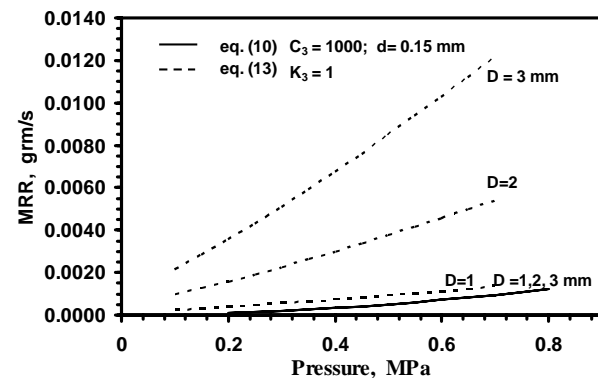


Fig. 12 Effect of pressure on material removal rate at different nozzle diameters for the two models  $\{\rho_a = 2.3 \text{ g/cm}^3; P = 0.5 \text{ MPa}; \eta = 0.7 \text{ and } \sigma_{fw} = 5000 \text{ MPa for glass}\}$

Air pressure in the range of 0.2 up to 0.8 MPa is used in the present work and it shows that the increase of air pressure makes it possible to remove material at higher rates.

Comparison between the prediction obtained by (10) and (13) are shown in Fig. 9. The results, shown in Fig. 9, demonstrate that the values of MRR have no difference at low pressure and small nozzle diameters. The difference between the predictions of the two models become noticeable when larger nozzle diameter ( $D=3 \text{ mm}$ ) is used as shown by solid and dotted curves.

This type of difference between the predictions of the two models as well as the experimental findings is shown in Fig. 10. It can be clearly shown that both models predict values for material removal rate less than the experimental values for the nozzle diameter less than 2 mm. When the nozzle diameter of 3 mm is used, the experimental value for material removal rate (MMR) is less than the theoretical prediction from both models  $\{(10) \text{ and } (13)\}$ .

The difference between the experimental and the theoretical values is mainly due to many sources of errors. The first type

of errors is mainly associated with the measurement techniques and their accuracies. The second source of errors is associated with the simplifications and the assumptions of the theoretical model. One aspect in the theoretical model is the velocity of air and the abrasive, i.e. the mixture of air and abrasive which is assumed to be equal to air velocity only which is obtained by Bernoulli equation (9).

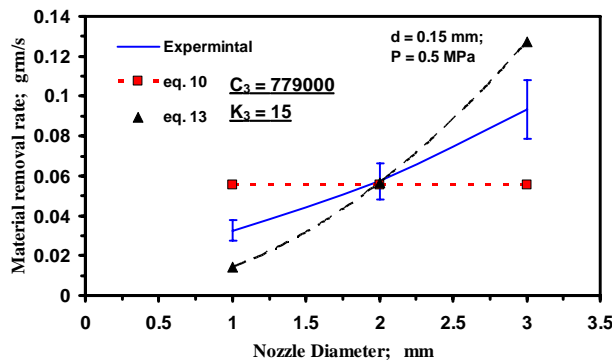


Fig. 13 Comparison between experimental and theoretical models at different nozzle diameter

The second aspect is the neglecting friction effect which reduces the velocity of the mixture (air + abrasive). This friction effect reduces the velocity and consequently, reduces the kinetic energy of the abrasive particles. Therefore, the lower prediction may be mainly due to these causes.

For bigger values of nozzle diameter ( $D=3$  mm) the flow rate of the mixture (air + abrasive) is high and this higher value compensates for the adverse effect of friction

The model predictions and the experimental findings are within  $\pm 20\%$  difference between each other. This might be considered as a reasonable result obtained by the available equipments and the assumed simplification of the proposed theoretical models.

## V. CONCLUSION

Experimental and theoretical analyses are introduced. The experimental and theoretical results obtained for material removal rates are close to each other within an error of not more than 20 percent which can be accepted for a mathematical model based on an erosion model. More experimental work and also more refinement for the theoretical model are needed to reduce the difference between the results as well as to introduce the neglected controlling parameters of the cutting process such as the cutoff distance.

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