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Cutting Fluid Aerosol from Splash in Turning: Analysis for Environmentally Conscious Machining

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The generation of airborne particulates from cutting fluids in machining operations poses a potential threat to machine operators. The primary mechanisms through which cutting fluid atomises to form liquid aerosol are splashing upon impingement on a solid workpiece, spin-off away from a rotating workpiece or tool, and evaporation due to high cutting temperature. This paper presents a quantitative model to describe the concentration and size distribution of aerosol resulting from the splash atomisation of cutting fluids in a lathe turning operation. In this analysis, the main parameters that govern the aerosol formation are the workpiece diameter, nozzle height, cutting fluid properties, and cutting fluid flow rate. The model first examines the fraction of splashed mass in relation to the total flow rate of cutting fluid based on the calibration of the splash parameter. The model further determines the statistical variation of the liquid droplet size due to unaccounted disturbances. The aerosol concentration is then expressed in terms of the product of the splash parameter and the fraction of total droplet volume of a specified size. The validity of the model is experimentally established based on light-scattering aerosol measurement carried out on a horizontal lathe with various jet heights, part diameters, and fluid flow rates. The results of this study can be used to estimate the amount of aerosol from a machining process, and to provide a quantitative basis for process optimisation, fluid planning, and machine design in achieving given environmental standards.

Keywords: Aerosol; Cutting fluid; Machining

1. Introduction

Cutting fluids are widely used in machining processes to cool the tool and part and to help remove chips from the cutting zone. Despite these benefits, the use of cutting fluids can present potential environmental problems. The waste stream of cutting fluids in the form of liquid aerosol may cause skin discomfort as well as respiratory diseases in operators. Poor air quality can lead to housekeeping safety concerns and cause fire on the introduction of sparks (most cutting fluids contains combustible oil) [1]. The current Occupational Safety and Health Administration (OSHA) limit for metalworking fluid mist concentration in a manufacturing environment is set at 5 mg m^{-3} as a permissible exposure level (PEL) for personnel [2]. This value was determined in 1970, and proposals to reduce the fluid PEL to 0.5 mg m^{-3} have been under review since 1998.

The primary mechanisms through which cutting fluid transforms itself into liquid aerosol in the surroundings are evaporation due to high cutting temperature, spin-off due to the tool or workpiece rotation, and splash motion associated with the impingement of the fluid jet on the tool, workpiece, or machine, under pressure [3]. There have been many studies of the liquid atomisation process in machining owing to liquid vaporisation and spin-off mechanisms. These studies include the work of Yue et al. [4], Bell et al. [3], Lefebvre [5], Bar [6], and Tanasawa et al. [7]. However, the study of liquid atomisation caused by the splash mechanism has been limited. The topic of jet impingement splashing is relatively new and little information is available as yet.

Most of the current analyses of jet impingement splashing have concentrated on the liquid jet impact on a flat circular plate, such as the studies performed by Lienhard et al. [8], and Ashgriz et al. [9]. In a machining process such as turning, the liquid jet impinges tangentially on the curved surface of a cylindrical workpiece. So far, there has been no model available to describe the aerosol generation caused in this impingement configuration and its associated fluid atomisation process. The scope of this paper is to describe quantitatively the cutting fluid aerosol generation process relevant to a turning operation performed on a horizontal lathe. It formulates a model in the context of impingement splashing and liquid atomisation to predict the formation of liquid aerosol resulting from splash. The model predicts the aerosol droplet concentration and size distribution as functions of workpiece diameter, nozzle to workpiece distance, cutting fluid properties, and fluid flow

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rate. The results of this study can be used to investigate the environmental impact of a machining process, or to offer a quantitative basis for process optimisation, fluid planning, and machine design. The development of the quantitative model and its experimental validation are given in the following sections.

2. Quantitative Modelling

Figure 1 shows the splash atomisation caused by the overhead application of cutting fluid in a turning process. In considering the mechanism of splash, the concentration of liquid aerosol containing droplets of diameter less than a certain size, D, can be defined as the amount, in weight, of droplets generated within a certain control volume after a certain duration of time, t, since the beginning of cutting fluid application:

$$\eta(t, D) = \beta\xi M\phi(D)t/\text{Vol} \quad (1)$$

where the β multiplier corresponds to the portion of the liquid jet involved in impingement. For the case of overhead cooling in horizontal turning, approximately half of the liquid jet impinges upon the cylindrical workpiece, therefore the β value is 0.5, ignoring the existence of the cutting tool. The parameters M and t are independent and explicit variables. In the following analysis, the parameter "Vol" is normalized to 1 m^3 for the calculation of aerosol concentration per m^3. The fraction of splashed fluids over total cutting fluids applied, as specified by ξ in Eq. (1), is related to a splash parameter, ω, defined as [10]:

$$\omega = W_e\left(e^{\frac{0.971l}{d\sqrt{We}}}\right) \quad (2)$$

where the Weber number W_e is given by

$$W_e = \rho u_f^2 \frac{d}{\sigma} \quad (3)$$

The splash parameter characterises the root-mean-square amplitude of disturbances, including air friction and in-flight evaporation, as the fluid droplets travel from the nozzle to the target surface. The relationship between the splash ratio ξ and the splash parameter ω has been experimentally identified in the work of Bhunia and Lienhard [10]. The apparatus used in their work consisted of a water tank, a tube, a flat end of a cylinder as the impact target, and a collector beneath the impact target. The amount of liquid that remained in the liquid sheet on the target after splashing was measured, while the splashed liquid remained airborne and fell well beyond the rim of the collector. For a known total fluid flow rate, a polynomial relation between ξ and ω was developed regressionally in the form of

$$\xi = C_1 + C_2\omega + C_3\omega^3 \quad (4)$$

In this study a similar experimental procedure was used to calibrate the coefficients C_1, C_2, and C_3 as described in Section 3.1.

The aerosol formation process can be affected by complicated uncertainties that are unaccounted for in the model. These uncertainties can cause the resulting droplet concentration and size to vary, therefore these aerosol attributes should be viewed as statistical variables. The distribution of the drop diameter can be described by probabilistic functions, such as the Rosin and Rammler cumulative distribution function [4], with respect to a mass median diameter D_m:

$$\phi(D) = 1 - \exp\left[-0.693\left(\frac{D}{D_m}\right)^{\delta}\right] \quad (5)$$

The mass median diameter is the droplet diameter such that 50% of the total liquid volume is in droplets of smaller diameter. From the work of Zhao et al. [11] and Lefebvre [5], the mass median diameter (D_m) and the distribution parameter, δ, are related to a Sauter mean diameter (SMD) by

$$\frac{D_m}{\text{SMD}} = 0.693^{1/\delta}\,\Gamma\left(1 - \frac{1}{\delta}\right) \quad (6)$$

where the coefficient 0.693 in Eqs (5) and (6) is a theoretical statistical constant. The Sauter mean diameter is the diameter of a droplet whose ratio of volume to surface area is the same as that of the entire spray.

In the splash atomisation process, the droplets are often observed to form immediately after the liquid jet impinges upon the workpiece. Therefore, it is assumed that the mechanics of the splash atomisation are similar to the drop mode atomisation process in a spin-off mechanism [8]. With this assumption, the Sauter mean diameter can thus be evaluated based on Tanasawa's formula [7] as

$$\text{SMD} = \frac{27}{N}\left(\frac{\sigma}{d_w\rho}\right)^{0.5}\left(1 + 0.003\frac{Q}{d_w\nu}\right) \quad (7)$$

in which N is the fluid angular velocity around the workpiece. To determine this angular velocity, it is necessary to calculate the linear velocity of the liquid jet at the impingement point. From the balance of potential and kinetic energies,

$$u_l = \sqrt{\left(2\left(gl + \frac{u_f^2}{2}\right)\right)} \quad (8)$$

Therefore, the fluid angular velocity can be expressed as

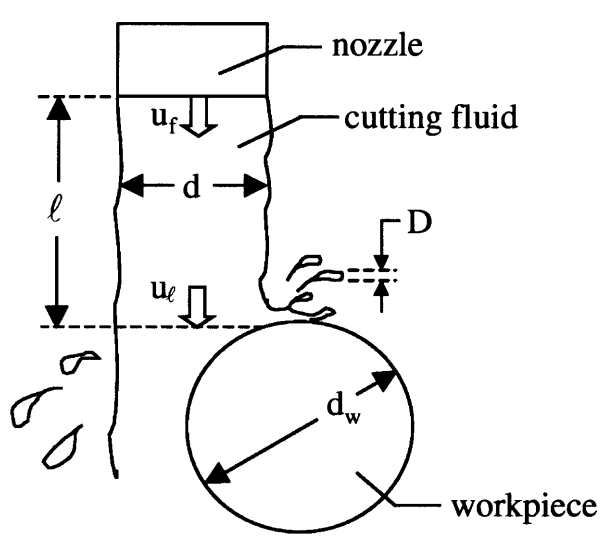

Fig. 1. Schematics of the cutting fluid splash process.

$$N = \frac{\sqrt{\left(2\left(gl + \frac{u_f^2}{2}\right)\right)}}{\pi d_w} \tag{9}$$

The distribution parameter, δ, provides a measure of the spread of droplet sizes. The factors expected to have a bearing on the spread of droplet sizes include in-flight disturbances, drop kinetic energy, and fluid properties. These factors are further dominated by the fluid velocity, workpiece geometry, and liquid viscosity. These variables can be combined in a dimensionless form as the Reynolds number under jet impingement conditions. In quantifying the effect of these variables, a general expression can be formulated to relate the distribution parameter and the Reynolds number, i.e.

$$\delta = KRe^n \tag{10}$$

With the Reynolds number defined as:

$$Re = \frac{u_l d_w}{\nu} \tag{11}$$

where K and n in Eq. (10) are constants that are determined empirically as given in the following section.

3. Experimental Calibration and Validation

3.1 Calibration of the Splash Ratio and Splash Parameter Relationship

The purpose of this experiment was to determine the relationship between the splash ratio, ξ, and the splash parameter, ω, for the model described in the previous section. Figure 2 shows the experimental set-up. Through a flexible tube, water (with density 1000 kg m^{-3}, surface tension 7.28×10^{-2} N m^{-1}, and kinematic viscosity 0.894×10^{-2} cm^2 s^{-1}) was delivered from a reservoir to a nozzle positioned at an adjustable height above the solid workpiece. The nozzle consisted of a diameter reducer and a straight tube section to create a fully developed cross-section of the fluid jet. The centreline of the nozzle pointed down toward the vertical tangent of the workpiece surface. The object of the test was to calibrate the model parameters under an environment independent of any machine tool system. The model developed in this manner can thus be validated without bias in an actual machine tool application, as described in Section 3.2.

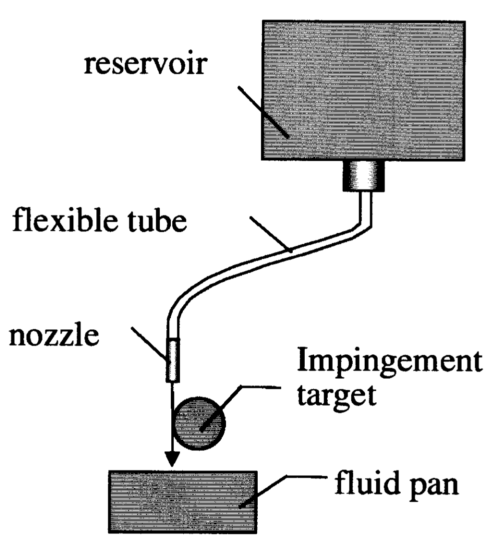

Fig. 2. Schematics of the calibration set-up.

The water released from the nozzle travelled through some distance in air and hit the workpiece surface to create splash. The portion of water not splashed was captured by a fluid pan situated underneath the workpiece. After a certain period of time, the fluid pan was weighed to determine the mass flow rate (M_c) of water captured by the pan. With the workpiece removed, the same experiment was repeated to determine the total water mass flow rate (M). These quantities divided by the water density, ρ, provided the volumetric flow rate of the fluids (Q_c) captured by the pan as well as the total volumetric flow rate of the cutting fluid (Q_t).

The difference between Q_c and Q_t led to the flow rate of the splattered liquid (Q_s). The process was repeated for different nozzle heights (l) to establish the relationship, shown in Fig. 3, that can be represented by $C_1 = 1.28 \times 10^{-2}$, $C_2 = 9.11 \times 10^{-5}$, and $C_3 = -6.00 \times 10^{-8}$ in a second-order polynomial form, given by Eq. (4), following from the work of Bhunia and Lienhard [10].

3.2 Calibration of the Distribution Parameter and Reynolds Number Relationship on a Machine Tool

To identify the relationship between the distribution parameter and the Reynolds number, a Data RAM 2000 particle counter was used to measure the aerosol concentration in the vicinity of the workpiece on a lathe (Hardinge T42SP), using water as coolant. The DataRam 2000 device is a nephelometric monitor whose light-scattering mechanism is configured for the measurement of aerosol concentration. By means of a diaphragm pump, air is pulled in through the inlet at speeds ranging from 1.7 to 2.3 m per min. Droplets passing through the light beam scatter light, which is sensed by a photodetector. Each optical signal is converted into an electrical pulse, which is processed electronically. The size of droplets determines the

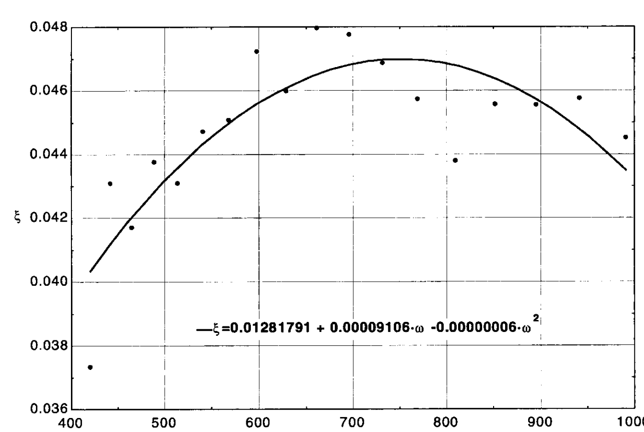

Fig. 3. Relationship between splash parameter (ω) and splash ratio (ξ).

Table 1. Experimental data for the calibration of K and n.

Data	d_w (cm)	l (cm)	Q_t (ml s^{-1})	$\bar{\eta}$ (kg m^{-3} s)	δ	R_e
1	4.2	2	77.0	0.619	1.676	35744
2	4.2	4	77.0	0.759	1.714	44313
3	4.2	6	77.0	0.734	1.764	50473
4	4.2	6	48.8	0.512	1.808	47911
5	4.2	7	48.8	0.507	1.837	51366
6	6.3	2	48.8	0.514	1.688	45584
7	6.3	6	48.8	0.560	1.822	71867

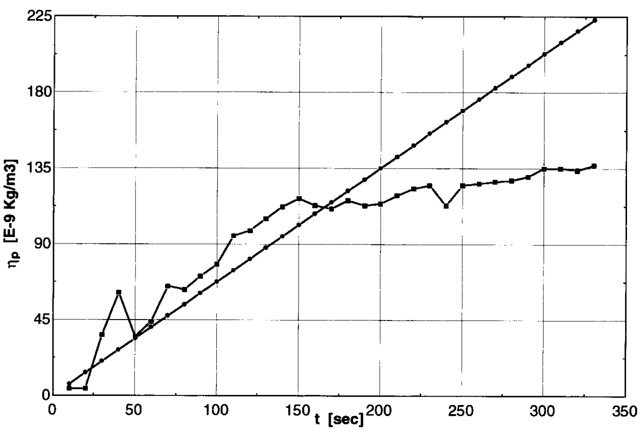

Fig. 4. Aerosol concentration for 4.2 cm workpiece diameter, 5 cm jet distance, and 48.8 ml s^{-1} cutting fluid flow rate. The curved line is experimental measurement and the straight line is the analytical prediction.

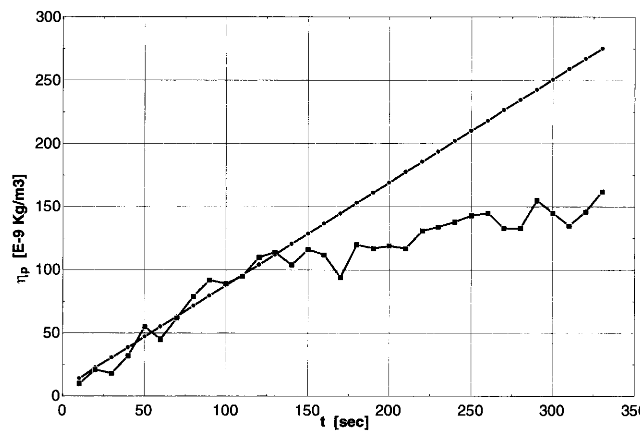

Fig. 5. Aerosol concentration for 4.2 cm workpiece diameter, 8 cm jet distance, and 48.8 ml s^{-1} cutting fluid flow rate. The curved line is experimental measurement and the straight line is the analytical prediction.

intensity of scattered light. Hence, the droplets may be sorted into various size classes according to their diameters. The measurement range covered from 0.1 μg to 400 mg m^{-3} in concentration and from 0.1 μm to 10 μm in droplet size. The term D_m in the predictive models was set to 10 μm for the purpose of comparison.

To rule out the possibility of evaporation and spin-off atomisation mechanisms in this experiment, the workpiece was not set in rotation and no cutting action took place in this series of experiments. The cutting fluid nozzle was pointed towards the workpiece with a downward trajectory, with the centreline of the fluid jet tangent to the side surface of the cylindrical workpiece. This experiment was performed repeatedly with different jet distance, workpiece diameter, and volumetric flow rate of the cutting fluid, as shown in Table 1. In each experiment, the average aerosol generation rate ($\bar{\eta}$) within the first 320 s of fluid application was recorded. From Eqs (1)–(9), the distribution parameter can be related to the average aerosol generation rate by

$$\ln\left(1 - \frac{\bar{\eta}\,(\mathrm{Vol})}{\beta\xi M}\right) = - \left(\frac{D}{\Gamma\left(1 - \frac{1}{\delta}\right)(27)\ \dfrac{\pi\sqrt{(d_w\sigma)}}{\sqrt{\left(2\left(gl + \frac{u_f^2}{2}\right)\rho\right)}} \left(1 + 0.003\,\dfrac{Q}{d_w\nu}\right)} \right)^{\delta} \tag{12}$$

based on which the distribution parameter, δ, is calculated for each case as shown in Table 1. Also listed in the table is the Reynolds number associated with each individual experimental condition. These Reynolds numbers and distribution parameters from the data sets were curve-fitted to obtain the parameters in Eq. (10). The resulting K and n values are 0.51893 and 0.11344, respectively.

To verify the validity of the model, additional data sets were obtained under process conditions different from the previous ones. The splash model was used to predict the aerosol concentration under these operating conditions. Figures 4 to 7 provide a comparison between experimental and model-predicted results. The irregular lines are the experimental measurements of aerosol concentration, and the straight lines are the model predictions. While the DataRAM measurement showed appreciable fluctuations owing to sensitivity to uncontrollable draught, agreement between the measurements and predictions can be observed.

4. Summary

In an effort to quantify the environmental effect of cutting fluids, a predictive model has been developed to describe the generation of airborne fluid particles due to splash atomisation in a horizontal turning process. In the model, the fraction of splashed mass, of the total mass flow rate of cutting fluid, is

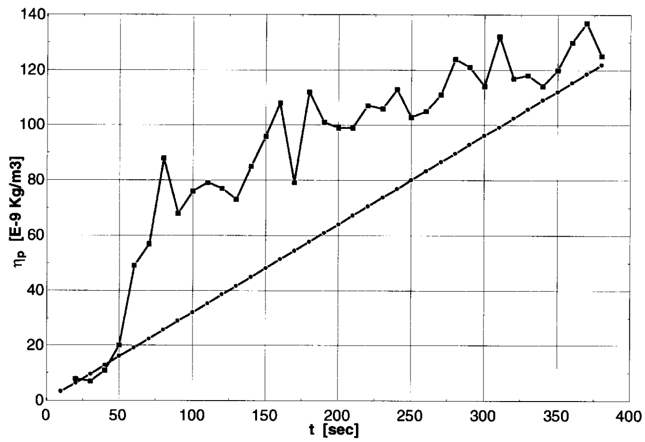

Fig. 6. Aerosol concentration for 6.3 cm workpiece diameter, 4 cm jet distance, and 48.8 ml s^{-1} cutting fluid flow rate. The curved line is experimental measurement and the straight line is the analytical prediction.

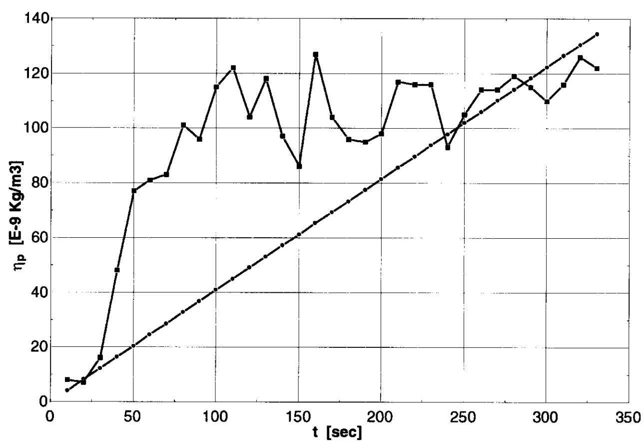

Fig. 7. Aerosol concentration for 6.3 cm workpiece diameter, 7 cm jet distance, and 48.8 ml s^{-1} cutting fluid flow rate. The curved line is experimental measurement and the straight line is the analytical prediction.

estimated from a splash parameter dependent on fluid properties, workpiece diameter, fluid flow rate, and jet height. The model also considers the possibility of unaccounted disturbances by expressing the cutting fluid droplet size distribution as a statistical variable in the Rosin and Rammler function, which is defined with respect to a Sauter mean diameter.

A jet-over-cylinder test was performed to calibrate the parametric relation between splash ratio and splash parameter. A series of tests were also performed on an actual horizontal turning machine to validate the model predictions. With a certain amount of scatter, the experimental measurements generally agreed with model predictions for the time evolution of aerosol concentration.

The resulting model can assist the estimation of environmental impact, in terms of air quality effect, of a machining process under specified operation parameters and process configuration. The predictive model can also be used to serve as a basis for process optimisation, fluid planning, and machine design for achieving given environmental thresholds.

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Notation

C_1, C_2, C_3	constants in the ξ and ω empirical correlation (dimensionless)
d	diameter of cutting fluid jet (m)
d_w	diameter of workpiece (m)
D	a specified diameter of liquid droplet (m)
K	constant in the R_e and δ empirical correlation (dimensionless)
l	distance from the jet nozzle to the impingement point on the workpiece (m)
M	total mass flow rate of the cutting fluids (kg s^{-1})
M_c	the amount of cutting fluid not splashed (kg s^{-1})
R_e	Reynolds number
D_m	mass median diameter (MMD) (m)
n	exponential constant in the R_e and δ empirical correlation (dimensionless)
N	fluid film angular speed around the workpiece (rev s^{-1})
SMD	Sauter mean diameter (m)
t	elapsed time since the liquid jet is started (s)
Q_t	total volume flow rate of cutting fluids (m^3 s^{-1})
Q_c	volumetric flow rate of the cutting fluids not splashed (m^3 s^{-1})
u_f	velocity of the cutting fluid jet at the nozzle exit (m s^{-1})
u_l	velocity of the cutting fluid jet at workpiece impingement point (m s^{-1})
Vol	one unit control volume (m^3)
W_e	Weber number (dimensionless)

β	fraction of cutting fluid cross-sectional area that impinges on the workpiece
$\underline{\eta}$	aerosol concentration (kg m^{-3})
$\dot{\eta}$	average aerosol generation rate (kg m^{-3} s^{-1})
δ	Rosin and Rammler distribution parameter (dimensionless)
η_{prod}	rate of aerosol generation (kg m^{-3} s^{-1})
η_{final}	experimentally measured final aerosol concentration (kg m^{-3})
$\eta_{ambient}$	ambient aerosol concentration level (kg m^{-3})
$\phi(D)$	fraction of the total volume of droplets of diameter less than D
ν	kinematic viscosity (m^2 s^{-1})
ω	splash parameter (dimensionless)
ρ	density of the cutting fluids (kg m^{-3})
σ	liquid surface tension (N m^{-1})
ξ	splash ratio, the fraction of splashed cutting fluids over total cutting fluids