AJChE 2020, Vol. 20, No. 1, 11-19

Effect of Venting on the Explosion of Aluminium-Silver Powder Mixtures

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Dust explosion is considered as a serious threat for the industry that use or handle combustible materials as it may lead towards a significant economic loss in terms of damage to the facilities and suspension of activities, severe workplace injuries and fatalities. The rapid pressure developed during a dust explosion can be mitigated by venting. The present work explored the effects of venting on the explosion of different mixing weight ratios of aluminium and silver powder mixtures. The explosion characteristics of aluminium-silver mixtures were assessed in a 0.0012 m^3 confined and vented cylindrical vessel. It was found that the application of 0.1 bar static burst pressure (P_{stat}) venting membrane gives one tenth reduction on explosion pressure and maximum rate of pressure rise for 70:30 and 50:50 mixing weight ratios of aluminium-silver mixtures explosion, respectively. This finding suggests that besides the venting application effect, the oxidation reaction of aluminium could be disrupted due to the presence of silver powder in the metal mixtures which results in lower heat transfer and reduction of the mass burning rate, hence, lessen flame speeds and explosion severity. However, the venting effectiveness is reduced when the P_{stat} increases. In order to assess the applicability of the dust explosion venting standard; NFPA 68 and EN 14491, the experimental results were compared with the calculated values according to the standards. The comparative results show that, both NFPA 68 and EN 14491 give underestimated values for explosion venting as compared with the experimental results.

Keywords: Explosion characteristics, Nanoaluminium, Nanosilver, Static burst pressure, Venting

INTRODUCTION

Dust explosion poses a critical threat for the industry that use or handle combustible materials as it may lead towards an extensive financial loss in

DOI: 10.22146/ajche.51850

terms of damage to the facilities and suspension of activities, severe workplace injuries and fatalities. Metal dusts present more challenges due to the hazard posed such as some combustible metal dusts have higher combustion temperatures as high as 4427°C and have higher deflagration index, K_{St}, than that of most organic dusts. Besides, combustible metal dust is water-reactive, electrically-conductive and able to react exothermically with oxides of other metals in a thermite reaction (Ibarreta and Myers, 2017). Metallic dusts contributed to a significant number of worldwide dust explosion statistics due their heightened ignition sensitivity and reactivity of the metal dust clouds in air. In 2010, a devastating metal dust explosion involving titanium and zirconium dust occurred in a metal producer in New Cumberland resulted in one serious injury and three fatalities (CSB, 2010). Another much more catastrophic explosion occurred in 2014, in Kunshan, China. An accumulation of aluminium alloy dust at a plant which mainly polishing surfaces of various metal parts, caused an explosion which led to 146 deaths, 185 injuries and direct financial loss of 351 million yuan (Li et al., 2016). Due to the hazards posed by metal dust, extensive studies have been conducted on their explosion severity. However, to this date, only explosion characteristics of single metal powder are widely available (Boilard et al., 2013, Jiang et al., 2011, Li et al., 2016, Li et al., 2011, Manju, 2014, Wu et al., 2010) yet, limited resources are available on the characteristics, behaviour and parameters when two or more metals are mixed. The big question would be at what extend the metal mixtures differ from the single metal explosion, particularly on pressure development during an explosion?

For industrial application, the rapid pressure buildup during dust explosion can be mitigated by venting. Venting aims to limit the internal overpressure developed during explosion in order for it to not exceed the enclosure strength. Literatures have demonstrated that venting effectiveness is influenced by some factors such as static burst pressure (P_{stat}) and vent diameter (Gao et al., 2016, Yan and Yu, 2014, Yan et al., 2015). Hence, an appropriate and reliable design of vent area concerning these factors is vital in order for venting to be effective in minimizing the overpressure developed during the explosion. Over the past decades, many empirical correlations and analytical models for vent design have been developed, some of which have been applied in the venting standards such as NFPA 68 (2018) (i.e. for USA) and EN 14491 (2012) (i.e. for Europe). These correlations were mainly derived from numerous huge scale testing enclosures with relatively low pressure bearing capacity such as silos and bag filter. These equipments usually have volumes larger than 0.1 m^3, low static activation overpressure lower than 1 bar and low maximum reduced overpressure (typically lower than 2 bar) (Yan and Yu, 2014). Nevertheless, industrial and technological development results in the necessity of protection for those relatively small vessels. Hence, this study aims to study the effect of venting on metal powder mixtures explosion and identify the applicability of the two different venting standards (i.e. NFPA 68 and EN 14491) on metal powder mixtures explosion in a small vessel.

METHOD

Materials

Two metal powders were used in this work, namely aluminium and silver powder. Aluminium powder with particle size 70 nm, as denoted in the subsequent paragraphs as Al 70 nm, and silver powder with particle size of 20 nm (denoted as Ag 20 nm) used in this work were purchased from Hongwu International Group Ltd and GetNanoMaterials, Oocap Inc, respectively. The sample powders are stored in a desiccator to remove excess moisture that might affect the experimental tests. The properties of metal powders are presented in Table 1.

Table 1. Physical and chemical characteristics of aluminium and silver particles

	Aluminium	Silver
Chemical formula	Al	Ag
Molar mass (g/mol)	26.98	107.87
Average particle size	70 nm	20 nm
BET surface area (m^2/g)	53.41	9.36

Experimental apparatus

The experimental apparatus, as presented in Fig. 1, comprises of a constructed 0.0012 m^3 stainless steel cylindrical test vessel with a mushroom-type nozzle similar to a typical Hartmann device, time controller (i.e. functions to keep the ignition time constant for all tests), a piezoelectric pressure transducer (Keller Series 11, accuracy: ±0.001 s), data acquisition system from National Instruments with a sampling rate of 100 MHz, and an ignition system consists of a pair of tungsten wire electrodes and a voltage transformer which give an ignition energy of 10 J. A gas nozzle was mounted on the vessel and connected to an air compressor for dust dispersion.

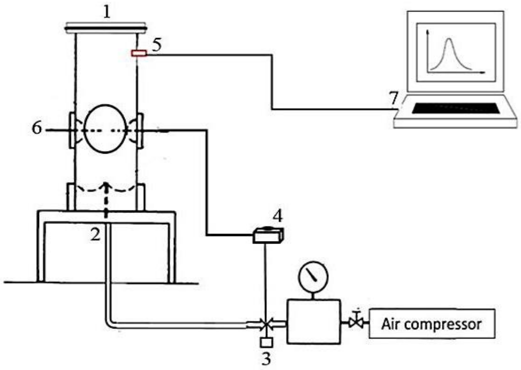

Fig. 1: Experimental apparatus. 1. Test vessel, 2. Gas nozzle, 3. Solenoid valve, 4. Time controller, 5. Pressure transducer, 6. Ignitor electrode, 7. Data acquisition system

Experimental procedures

Dust explosion in confined vessel

Six powder concentrations (i.e. mass of powder/volume of vessel) were used in the experimental works; 300 g/m^3, 500 g/m^3, 700 g/m^3, 900 g/m^3, 1200 g/m^3 and 1500 g/m^3. Aluminium nanopowder were weighed into the weighing balance at different powder concentrations. Silver powder of 20 nm was then well-mixed with the Al 70 nm at 70:30, 50:50 and 40:60 mixing weight ratios. The aluminium-silver (Al-Ag) was placed in the dispersion cup and the test vessel was tightened up. An ignition spark was initiated with 60 ms delay time after the mixtures was dispersed by using 6 bar pressure of air compressor. The ignition delay (t_v), i.e., the time between the onset of dust dispersion and the ignition of the dust-air mixtures, was set at 60 ms in accordance with ASTM E1515/EN14034. Further experimental works were conducted at different aluminium powder concentrations (i.e. 300 g/m^3, 500 g/m^3, 700 g/m^3, 900 g/m^3, 1200 g/m^3, 1500 g/m^3) to study the effect of powder concentration on explosion pressure development. Each experiment was carried out repeatedly for at least three times for accuracy and reproducibility. The standard deviation for each of the results are within the range of 0.02 – 0.15, indicating that the data spread was closer to the mean values and reproducible.

Dust explosion in vented vessel

In the experimental works conducted in vented vessel, the vent cover of 0.1 static burst pressure (P_{stat}) was placed and tightened on top of the test vessel prior to the dust explosion tests. Next, aluminium was weighed at 300 g/m^3 and mixed with silver powder at 70:30, 50:50 and 40:60 mixing weight ratios. After the placement of the Al-Ag mixtures in the test vessel, compressed air of 6 bars was used for powder dispersion and the powder was ignited after 60 ms time delay, t_v. Further experiments were conducted on the different aluminium powder concentration at P_{stat} of 0.3 and 0.5 bar. Repeatability and accuracy were confirmed by conducting at least 3 times. The standard deviation for each of the results are within the range of 0.02 – 0.15, implying that the data spread was closer to the mean values and reproducible.

RESULTS AND DISCUSSION

Explosion characteristics of Al-Ag metal mixtures

The maximum explosion pressure (P_{max}) and the maximum rate of pressure rise (dP/dt_{max}) values of three mixing weight ratios of aluminium and silver mixtures corresponding to aluminium powder concentration is presented in Fig. 2.

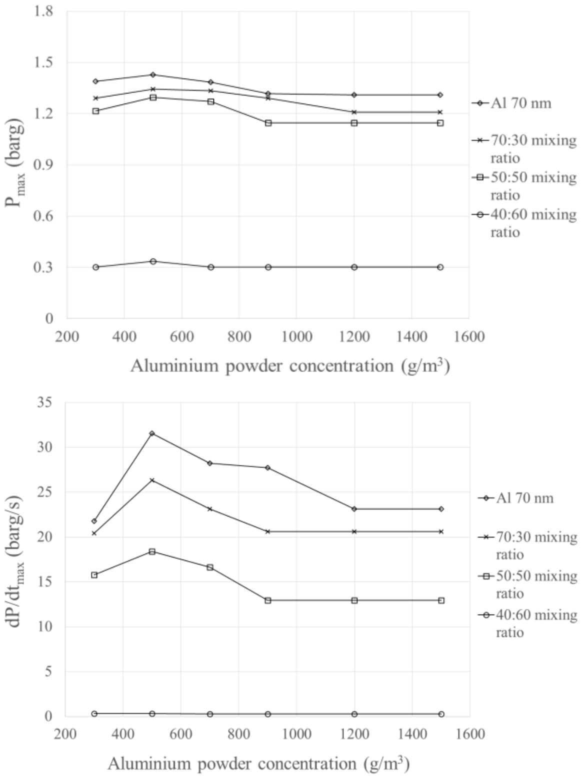

Fig. 2: P_{max} and dP/dt_{max} of Al-Ag mixtures in confined vessel

The addition of silver particles to Al 70 nm resulted in the reduction of the P_{max} values. The addition of 30% and 50% weight (% wt.) of silver particles causes the P_{max} and dP/dt_{max} values of Al 70 nm decreased about 13% and 16%, respectively. For instance, at 500 g/m^3 of aluminium powder, the P_{max} and dP/dt_{max} values for 70:30 and 50:50 mixing weight ratios are 1.34 barg and 1.297 barg, respectively, as compared to that of 1.43 barg recorded at pure aluminium powder. Meanwhile, at 40:60 mixing weight ratio of Al-Ag mixtures, the P_{max} value of the mixtures decreased approximately one fifth of the value recorded at Al 70 nm.

It is noteworthy that both P_{max} and dP/dt_{max} values of all mixing weight ratios of Al-Ag mixtures increases with increasing aluminium powder concentration. For instance, an increase of approximately 7% and 17% of P_{max} and dP/dt_{max} values were observed at 50:50 mixing weight ratio of Al-Ag mixtures, respectively, when the aluminium powder concentration increased from 300 g/m^3 to 500 g/m^3. However, it was found that when the powder concentration is higher than 700 g/m^3, the P_{max} and dP/dt_{max} values of the mixtures are significantly decreased. A constant value of both P_{max} and dP/dt_{max} were demonstrated at high aluminium powder concentrations (i.e. 900 g/m^3 – 1500 g/m^3). This observation may be attributed to the effect of adding the silver powder in the metal-metal mixtures explosion and the reduction of inter-particles distance at highly loaded aluminium powder. At aluminium powder concentration between 900 g/m^3– 1500 g/m^3 , it was claimed that the inter-particles distance reduces due to the increasing number of particles per unit volume, leading to the reduction of heat transfer efficiency (Dufaud et al., 2010, Mishra and Azam, 2018). Whilst, the presence of silver powder would disrupt the overall of aluminium oxidation reaction. In consequence, the mass burning rate and flame speed would be reduced due to the slower heat transfer resulted from the disruption of oxidation reaction, and hence, gives quite a substantial effect on the explosion severity (Mohd Mokhtar et al., 2019). These combined factors cause the constant values of P_{max} and dP/dt_{max} were attained at higher aluminium powder concentrations (i.e. 900 g/m^3 – 1500 g/m^3).

Effect of venting on explosion severity of Al-Ag mixtures

The effect of venting application on the explosion severity of Al-Ag mixtures were demonstrated in Fig. 3. The application of 0.1 bar static burst pressure (P_{stat}) venting membrane results in approximately one tenth reduction of explosion pressure and dP/dt_{max} of the 70:30 and 50:50 mixing ratios of aluminium-silver mixtures, respectively. Meanwhile, the explosion severity of 40:60 mixing weight ratio of Al-Ag mixtures decreased approximately 85% as compared to the values recorded in the confined vessel (refer to Fig. 2). Additionally, Fig. 3 also shows about 30% reduction of the reduced explosion pressure (P_{red}) and dP/dt_{max} values of pure aluminium powder when 50%wt. of silver powder was added in the Al-Ag mixtures. Meanwhile, the addition of 60% weight of silver powder at 500 g/m^3 of Al 70 nm results in 50% decrease of P_{red}. In addition to the effect of silver particles (as stated in the previous section), the effect of venting application results in significant reduction of the explosion severity of the Al-Ag mixtures.

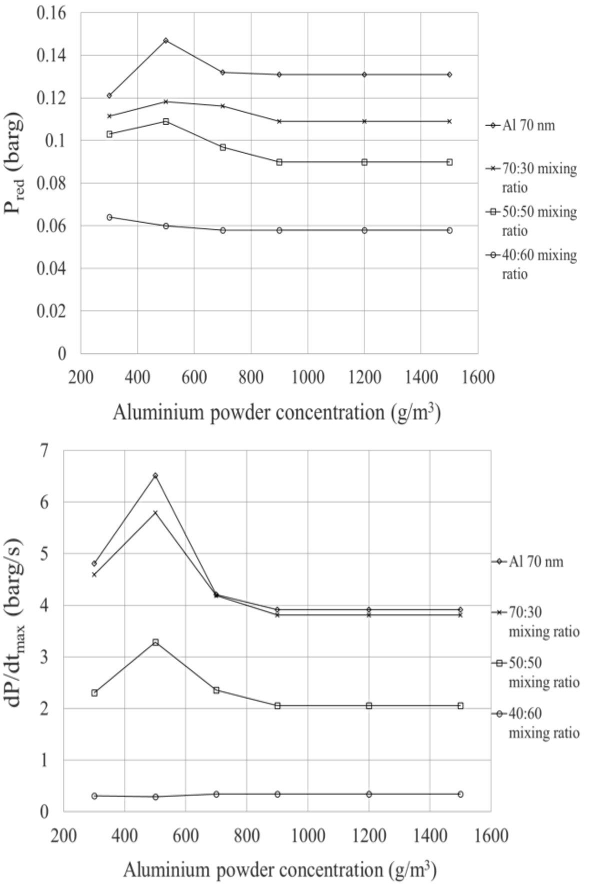

Fig. 3: P_{red} (top) and dP/dt_{max} (bottom) of Al-Ag mixtures in vented vessel

However, the venting effectiveness is reduced when the P_{stat} increases, as demonstrated in Fig. 4. The graphical representation of the relationship between the P_{stat} and P_{red} of Al-Ag mixtures in Fig. 4 demonstrated that, by increasing P_{stat}, the P_{red} values of both Al 70 nm and Al-Ag mixtures increased, respectively. The increment of P_{red} value is more significant when the P_{stat} increases from 0.1 bar to 0.3 bar. The P_{red} value of Al 70 nm and Al-Ag mixtures at P_{stat} of 0.3 bar increased approximately four times the values recorded for P_{stat} at 0.1 bar. Meanwhile, the P_{red} values at P_{stat} of 0.5 bar increased approximately 20% from the values recorded on the P_{stat} at 0.3 bar. An increase of P_{stat} results in a delay of venting process, hence reducing the venting effectiveness (Gao et al., 2016). This signifies the reduction of dP/dt_{max} of Al 70 nm and Al-Ag mixtures at P_{stat} of 0.5 bar, as compared to the values recorded at P_{stat} of 0.3 bar shown in Fig. 4(b).

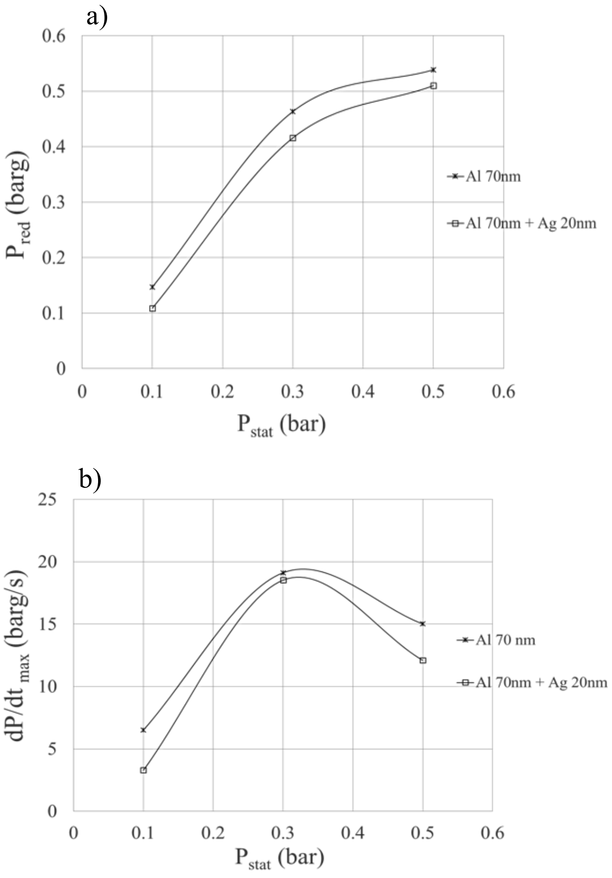

Fig 4. P_{red} (top) and dP/dt_{max} (bottom) of Al-Ag mixtures corresponding to various P_{stat}

Applicability of the dust explosion venting standard

Evaluation of the applicability of vent sizing equations in NFPA 68 and EN 14491 is based on the experimental results in Fig. 4 and experimental findings from literatures. The vent areas (i.e. $A_{v\text{-}NFPA\ 68}$ and $A_{v\text{-}EN\ 14491}$) have been calculated by using Eqs. (2) and (3), for different P_{stat}.

$$A_{vNFPA68} = 10^{-4}\left(1+1.54{P_{stat}}^{4/3}\right)K_{st}\cdot V^{3/4}\sqrt{\frac{P_{max}}{P_{red}}-1} \quad (1)$$

$$A_{vEN14491} = \left[3.264\times 10^{-5}P_{max}\cdot K_{st}\cdot {P_{red}}^{-0.569} + 0.27(P_{stat}-0.1){P_{red}}^{-0.5}\right]V^{0.753} \quad (2)$$

where:

$A_{v\text{-}NFPA68}$ = vent area calculated from NFPA 68 equation (m^2)
$A_{v\text{-}EN\ 14991}$ = vent area calculated from EN 14991 equation (m^2)
P_{stat} = nominal static burst pressure of vent (bar)
K_{st} = explosion index ($bar{\cdot}m{\cdot}s^{-1}$)
V = enclosure volume (m^3)
P_{max} = maximum explosion pressure (bar)
P_{red} = reduced explosion pressure (bar)

It is noteworthy that the conditions in this work are slightly differed from those required in the venting standards. The differences between the conditions used in this experimental works and those stated in the standards is presented in Table 2. It can be observed that the enclosure volume is beyond the applicability of the equations. Hence, the experimental results of this work were compared with the values calculated using both standards and calculated values from literatures, to study the robustness and the extendibility of the equations. The ratios of the calculated vent area to the experimental vent area ($A_{v\text{-}exp}$) of this work were plotted in Fig. 5. When the ratio of the calculated vent area to the actual experimental vent area is more than 1, it means that the calculated vent area using the venting standards were larger than the actual vent areas, and vice versa.

As shown in Fig. 5, the ratio of A_{vcal}/A_{vexp} in the present study is less than 1 indicating that both standards give underestimated vent area values. Referring to the study conducted by Jiang et al. (2018), the ratio of A_{vcal}/A_{vexp} using Eq (1) was demonstrated to close to 1, indicates that NFPA 68 gives a better prediction on vent area, hence it is more conservative in the case of that study. It is depicted that vessel volume plays a vital role in the applicability of these standards, besides the other parameters. Hence, an extensive study needs to be conducted to further study parameters affecting the venting of metal powder mixtures explosions in a relatively small vessel.

Table 2. Differences between conditions in experimental works and requirements in the venting standards

Parameter	NFPA 68	EN 14491	This work	Ji et al. (2018)
Enclosure volume, V	0.1–10,000 m^3	0.1–10,000 m^3	0.0012 m^3	0.02 m^3
P_{stat}	<0.75 barg when $P_{initial}$ is <0.2 barg	0.1–1 bar	0.1–0.5 bar	1.32 – 1.5 bar
P_{red}	Not stated	P_{stat} ~ 2 bar	0.11– 0.47 barg	0.87–6.12 bar
Explosion index, K_{st}	10–800 $bar{\cdot}m{\cdot}s^{-1}$	10–800 $bar{\cdot}m{\cdot}s^{-1}$	1.96 $bar{\cdot}m{\cdot}s^{-1}$	103.5 $bar{\cdot}m{\cdot}s^{-1}$
Atmospheric pressure	0.8–1.2 bar	0.8–1.1 bar	1.0 bar	1.01 bar

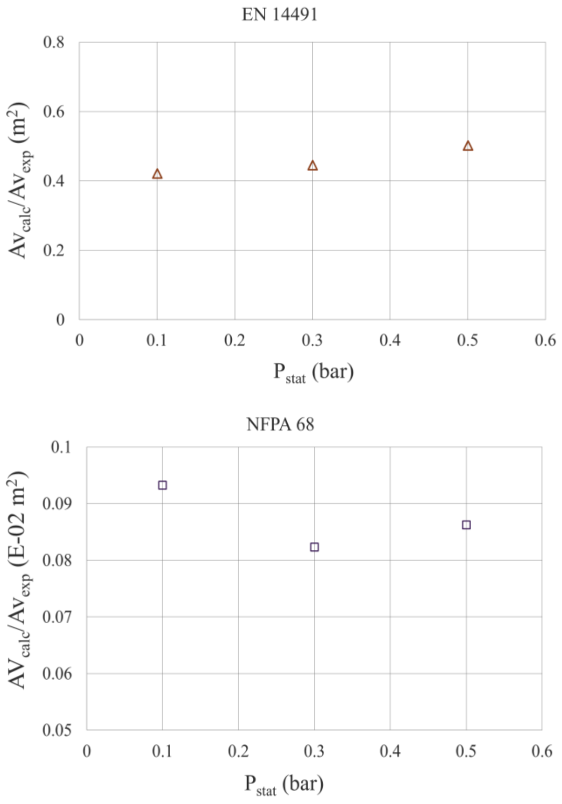

Fig 5: Comparison of vent area calculated using EN 14491 (top) and NFPA 68 (bottom)

CONCLUSIONS

The present research work explored the explosion characteristics of different mixing weight ratios of aluminium and silver mixtures in confined vessel and vented vessel. The most significant reduction of P_{max} value can be observed with the presence of 60%wt. ratio of silver powder, which the P_{max} value of Al 70 nm decreased approximately 78%. There is no significant effect of aluminium powder concentration on both P_{max} and dP/dt_{max} of Al-Ag mixtures when the powder concentration is between 900 g/m^3 to 1500 g/m^3 due to the reduction of inter-particles distance at highly loaded powder and the effect of the silver powder. In addition to the effect of the silver particles, the venting application results in reduction of the explosion severity of the Al-Ag mixtures ~ 85 %. Nevertheless, the venting effectiveness is lowered when the P_{stat} increases. Despite of this finding, comparative studies between experimental results and venting standards (i.e. NFPA 68 and EN 14991) demonstrated underestimated values regardless of the P_{stat} effect, hence, indicated that both standards are inapplicable in case of the present study.

ACKNOWLEDGEMENT

This research was funded by University of Malaya [Grant No.:GPF065A-2018], and Universiti Teknologi Malaysia [Tier 1 Grant No.: Q.J130000.2546.14H41].

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