Energy Saving and Pollutant Emission Reduction by Adding Hydrogen in a Gasoline-fueled Engine

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ABSTRACT

Pollution reduction related to combustion engines is considered to be an important issue around the world. Hydrogen as an additive energy has been utilized for alternative fuel since it need not require any modification. Particularly, it has been considered as a sustainable option for diminishing petroleum dependence and air pollutant emissions. In this study, we investigated the tailpipe emission with hydrogen addition for different driving behavior such as cold-start, idle, urban (UDC) and extra-urban (EUDC) under New European Driving Cycle (NEDC). The results showed that urban driving could attribute the most emissions in comparison to the high speed mode. Hydrogen addition enhanced the combustion process and the average reduction rates were observed 21.6% and 65.8% for hydrocarbon (HC), 2.37% and 85.4% for carbon monoxide (CO), and 7.53% and 59.3% for nitrogen oxides (NOx) when run at UDC and EUDC, respectively. The wide flammability of hydrogen ensures a homogeneous fuel-air mixture for complete combustion and reduces the HC, CO and NOx emissions. It is noteworthy that starting with less amount of hydrogen could greatly decrease HC followed by CO and NOx. Compared to conventional gasoline (G0), the average fuel consumption was reduced by 1.3% when a small amount of hydrogen was applied as an additive fuel.

Keywords: Hydrogen, Gasoline, Pollutant emission, Cold-start condition, NEDC driving cycle

1 INTRODUCTION

It is a well-known that, the limitation of global energy resources and severe air pollution from fossil fuel have led to urgent concern around the world (Chen et al., 2017). The global oil consumption from transportation sector accounts for about 50%, nearly 25% of CO2 derived from traffic-related emissions (Chang et al., 2017). The rapid increase of fossil fuel consumption such as petroleum, natural gas, and coal has given to a sharp rise in fuel prices at the present scenario. The combustion of those fossil fuels can generate enormous air pollutants such as Hydrocarbon (HC), Particulate Matter (PM), Carbon Monoxide (CO), Carbon Dioxide (CO2), Nitrogen Oxides (NOx), Sulfur Oxides (SOx) and toxic metals which are causing many environmental problems and negative
health effects (Liu et al., 2017; Sakthivel et al., 2020; Wu et al., 2020). Many people suffered from high traffic contamination exposure when they stay in the near road, stop at a traffic light or spend time during heavy traffic circumstances (Tsai et al., 2020; Yu et al., 2021). Also, the traffic-related air pollutants could be considered as critical issues related to human health (Tsai et al., 2020; Zhang et al., 2022).

Hydrogen, as an additive energy is being utilizing for alternative fuel in combustion engine since it need not require any intense engine modification. Especially, hydrogen have been considered as sustainable options for diminishing petroleum- dependence and air pollutants emissions (Chang et al., 2017). Concerning on both limited fossil fuel and severe air pollution issues, hydrogen as an additive energy is able to improve engine efficiency and diminish the regulated and unregulated pollutant emissions (Chen et al., 2017; Jhang et al., 2018, 2016). Hamdan et al. (2015) has been stated that injecting small amount of hydrogen in diesel engine not only decreases the heterogeneity of diesel fuel spray but also reduces the combustion duration.

Yang and Ji (2018) investigated the performance of a gasoline engine fueled with hydrogen/gasoline and observed an increase in break thermal efficiency and reduced emissions in HC and CO. During the first 19 seconds of cold start phase, the shortened flame development and propagation periods can be found when the hydrogen flow rate rises from 0 to 3.15 L min⁻¹. The HC, CO and particulate number are reduced by 68.7%, 75.2% and 72.4% during cold-start conditions, respectively (Zhang et al., 2014).

Therefore, the results obtained from the above studies are mentioning that, the hydrogen as an alternative additive fuel is more applicable to use in vehicle engines (Akal et al., 2020; Elsemary et al., 2017, 2016). However, it is worth to note that the characteristics of hydrogen contains high energy and low density which requires large loading volume. Although, it can be stored in several ways such as compressed gas, cryogenic liquid or as a gas dissolved in metal hydrides but there still exists the limited facility and insufficient evidence in the current situation. For instance, overweight of hydrogen containers, the cost of liquefied hydrogen, insufficient urban infrastructure for refilling and the risk of storing including carrying hydrogen in vehicles.

In order to overcome this issue, one method is to generate the hydrogen on-board by using water electrolysis hydrogen generator. The hydrogen is extracted from water by using very less power to operate, which provides a continuous amount of hydrogen to reach the engine combustion chamber through the air inlet manifold (Chen et al., 2017). The layout has the benefit since the hydrogen provides followed by the vehicle starting up and running and finished as the engine is switched off. Therefore, the storage is not necessary which has reduced the risk of explosion (Jhang et al., 2016).

Although several researchers have studied about hydrogen on-board through water electrolysis (Bari et al., 2022; Martin et al., 2019; Rodriguez Matienzo, 2018), however, the analyzer measurements in the instantaneous emissions under standard New European Driving Cycle (NEDC) is still sparse and a very few studies discusses the use of hydrogen as an additive fuel during cold start or idle operation. The energy saving and pollutant emission reduction of hydrogen–gasoline dual-fuel were compared with that of conventional gasoline (G0).

## 2 METHODS

### 2.1 Experimental Setup and Procedure

The study is planned to investigate the effect of small amount of hydrogen on a light-duty gasoline vehicle. The test was carried out at the Refining and Manufacturing Research Center for light-duty vehicle test research center (Chinese Petroleum Co., Chia-Yi, Taiwan). Fig. 1 presents the schematic of the experimental setup for the vehicle test system. The apparatus of driving test include gaseous emission analyzer (Horiba, MEXA-7400LE), single roll chassis dynamometer with constant volume sampler (Horiba constant volume sampler, CVS 7200 s). The gas analyzers are consist a chemiluminescent detector (CLD), non-dispersive infrared (NDIR) detector and flame ionization detector (FID) for HC, CO and NOₓ, respectively (Table S1). The detail of chassis dynamometer system is displayed in Table S2.

In this study, a commercial hydrogen generator (GOC HGL-600 H/U) was engaged to produce a continuous stream of hydrogen (purity higher than 99.99%). A gas flow meter was installed
which not only regulates the hydrogen stream and detects the purity of hydrogen (purity higher than 99.99%), but also includes a flame arrester to restrain immature explosions. To speed up and simplify the setup, the produced hydrogen is powered by 24 V external power supply, with a maximum hydrogen production capacity of 1 Nm$^3$ hr$^{-1}$. Vehicle carrying large amount of hydrogen could bring extra weight and make it dangerous for storage. Small hydrogen-volume fraction would be more suitable for safer application and less carrying weight (17.5 kg) for the conventional gasoline vehicle. Therefore, pure hydrogen with volume fraction of 0.6 and 1.2 L min$^{-1}$ have been considered in this study. Hydrogen was produced and fed into manifold, accompanied by the engine starting up, running and finished as the engine switched off. This indicates the storage is not required since the produced hydrogen can be consumed immediately and this reduces the risk of explosion (Bari et al., 2022; Jhang et al., 2020, 2016).

The speciation of vehicle is shown in Table S3. The vehicle used in this experiment for the test is Peugeot 406. NEDC is a driving cycle designed to evaluate the emission level as well as fuel economy in passenger cars. The test procedure is accomplished on a chassis dynamometer composed of four UDC and one EUDC. UDC is representing the typical city driving conditions such as low vehicle speed, engine load and exhaust temperature. In contrast, the EUDC is designed to the extra-urban roads with high speed driving mode which can reach to the maximum speed of 120 km h$^{-1}$. The detail of test cycle was shown in Table 1. According to the pre-treatment process, vehicle should be driving over NEDC cycle and then soak for at least 6 hours under the temperature of 20–30°C. Afterwards, the engine start with gasoline, then the hydrogen will introduce into the gas flow meter to ensure the hydrogen flow rate through the air inlet manifold (Armas et al., 2016; Ji et al., 2013).

We defined the first 100 seconds as cold-start duration under UDC test cycle. The accumulated mass of engine cold-start was conducted by using the following Eq. (1):
Table 1. The summary for NEDC (UDC + EUDC) driving test.

<table>
<thead>
<tr>
<th>Items</th>
<th>UDC</th>
<th>EUDC</th>
<th>NEDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>0.9941</td>
<td>6.9549</td>
<td>10.9314</td>
</tr>
<tr>
<td>Total time (s)</td>
<td>780</td>
<td>400</td>
<td>1180</td>
</tr>
<tr>
<td>Idle time (s)</td>
<td>57</td>
<td>39</td>
<td>267</td>
</tr>
<tr>
<td>Mean speed (km hr⁻¹)</td>
<td>18.35</td>
<td>62.59</td>
<td>33.35</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>50</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

\[ M_i = \sum_{t=100}^{100} C_i \cdot Q \cdot \Delta t \]  

(1)

where \( M_i \) represents the amount of exhaust pollutants (g) from the vehicle under cold-start duration \( t \) (s). \( C_i \) expresses the concentration (g m⁻³) of pollutants (i). The volumetric flow rate is expressed in \( Q \), it represents the instantaneous exhaust flow rate (m³ s⁻¹).

3 RESULTS AND DISCUSSION

3.1 The Effect of Hydrogen Addition on Fuel Consumption

Fig. 2 displays the distributions of fuel consumption with and without hydrogen addition under three operating modes (UDC, EUDC, and NEDC). The decrease of the fuel consumption is observed with the increase of the hydrogen sent into the cylinder. As the 0.6, 1.2 L min⁻¹ hydrogen flow rate pumped in, the average fuel consumption reduction is observed as 1.36%, 1.32%, and 1.31% under UDC, EUDC, and NEDC phases, respectively. The effect of hydrogen–gasoline mixtures took place with the wide flammability than the one of original gasoline fuel which results in complete combustion and causes better combustion quality (Karagöz, 2019; Liu et al., 2017).

3.2 The Effect of Hydrogen Addition on HC, CO and NOₓ Emission

Fig. 3(a) shows the hydrogen carbon (HC) of the three operating modes (UDC, EUDC, and NEDC). The emission factor of UDC, EUDC, and NEDC with base fuel of G0 are 0.0892 g km⁻¹, 0.217, and 0.0161 g km⁻¹, respectively. Compared to EUDC phase, UDC contributes most of HC emissions because of cold-start procedure (Duan et al., 2017; Zhu et al., 2018). Hydrogen addition of 0.6 and 1.2 L min⁻¹ enhances the combustion process, it is reduced by 18.4%, 62.7%, and 24.8%, 68.9% when run at UDC and EUDC, respectively. The flexible characteristics of hydrogen contents short quenching distance, wide flammability and also extends the homogeneous fuel-air mixture during cold-start conditions, which enhances the less fuel consumption. The results also suggest that the replacement of carbon-based fuel with non-carbon fuel by using hydrogen decreases...
unburnt HC emissions based on the mechanism of combustion process when blend with hydrogen. The reactivity process can be improved due to the chemical reaction of \( R_1 (H + O_2 \leftrightarrow OH + O) \) and \( R_2 (OH + H_2 \leftrightarrow H_2O + H) \) which produce H and OH radicals. It accelerates oxidation rates and the pollutants species, implying the lower activation energy tend to produce those radicals and break down H\(_2\) compound. Also, the faster reaction rate of H\(_2\) pyrolysis could further oxidize the CO and HC. These results are found in consistent with those reported by Ref. (DeAlmeida et al., 2015; Jhang et al., 2016; Ji et al., 2016a).

Fig. 3(b) depict the CO emissions of the three operating modes (UDC, EUDC and NEDC). The emission factor of NEDC with base fuel of G0 is 1.53 g km\(^{-1}\). Similarly, 0.165 and 0.664 g km\(^{-1}\) are the emission factors for UDC and EUDC, respectively. Carbon monoxide is colorless, odorless, tasteless and toxic which generates under incomplete combustion (Jhang et al., 2016; Sharma and Dhar, 2018). The diffusivity of hydrogen is higher than gasoline vapor, it supports homogeneous fuel-air mixture throughout the combustion chamber. In this study, blending gasoline fuel with hydrogen can decrease the CO emissions. The average reduction at UDC and EUDC with increasing amount of hydrogen are 2.36% and 85.4%, respectively.

With respect to NO\(_x\) in Fig. 3(c), the emission factors of UDC, EUDC and NEDC with base fuel of G0 are 0.657, 0.613 and 0.629 g km\(^{-1}\) respectively. It also shows that at different driving conditions, the NO\(_x\) emissions during UDC are higher than EUDC operation. In general, NO\(_x\) emission directly
related to cylinder temperature as well as abundant oxygen supply (Rajak et al., 2020; Zhu et al., 2018). Therefore, the UDC contributes most of NOx emissions because of the cold-start procedure in comparison with EUDC phase.

Several researchers mention that hydrogen addition could increase NOx level, however within the part load with low levels of hydrogen addition can decrease the NOx emissions (Sharma and Dhar, 2018; Su et al., 2018). Nitrogen oxides (NOx) contains both nitric oxide (NO) and nitrogen dioxide (NO2), while NO2 can be considered as minor contributor. Hydrogen addition increases HO2 radical due to the reaction of R3 (H + O2 +M ↔ HO2 + M). HO2 can behave as terminator which tend to decrease NO by the reaction of R4 (NO + HO2 → NO2 + OH). Therefore, the low level of hydrogen addition is accessible to the growth of HO2 radicals. In this study, we observe this trend under UDC, EUDC and NEDC with small amount of hydrogen addition. As the 0.6, 1.2 L min⁻¹ hydrogen flow rate pumped in, the average reduction over UDC, EUDC and NEDC are 7.53%, 59.3% and 39.5% in comparison with base fuel of G0.

3.3 Temporal Variation of HC, CO and NOx Emissions over Cold-Start and NEDC Driving Cycle

The temporal variation of HC emission concentrations with and without hydrogen addition are shown in Fig. 4. As observed during first start up, the increasing pressure of combustion chamber lead to unburnt fuel emitted from combustor and crevices. It is observed that unburnt hydrocarbons show an increasing trend owing to the high residual gas and inherent low temperature combustion which is considered as major drawback of engine start up (Karag, 2019; Pacheco et al., 2013). Another reason can be attributed to the high combustion rate of hydrogen which consumes the adjacent air very quickly and thus leads to lean area. Finally, it can be found that the gas emissions increase during the first accelerating phase. Similar results have been observed when the driving

Fig. 4. The instantaneous HC emissions with hydrogen addition under NEDC driving cycle. Subplot represents the duration of cold-start.
behavior such as climbing a hill, quick deceleration and rapid vehicle acceleration lead to maximum engine power which could create unburned HC significantly (Alves et al., 2015). In Fig. 4, the higher HC emission is slightly decreased when it is applied with fuel blend of hydrogen. It is observed that starting with less amount of hydrogen can decrease the engine cold-start emissions due to the non-carbon fuel of hydrogen (Hao et al., 2016). It can also be found that the emission of vehicles with hydrogen addition is always lower than that of vehicles with base fuel of gasoline exhaust. The increase of HC emission is greatly decreased and remained at lower level during UDC and EUDC periods. The observations in this study are similar to those reported in the literature (Gutarevych et al., 2018; Hao et al., 2016; Ji et al., 2013).

Fig. 5 shows the time series variation of CO emission concentration with and without hydrogen addition. Similar to the THC variation, the strong fluctuations can be found in the UDC period and less in the EUDC. The higher CO emission concentration peak at first start-up condition is because of the insufficient amount of air and time for complete combustion. The result also shows that the peak value decreases with hydrogen addition of 0.6 and 1.2 L min⁻¹. Starting by less amount of hydrogen, it decreases the engine cold-start emissions of HC and CO. The wide flammability of hydrogen ensures homogeneous fuel-air mixture to be completely burnt during driving cycle. Similar results are reported by Refs. (Karag, 2019; Zhang et al., 2014).

Fig. 6 shows the NOx emission concentration with time. It is not similar to THC and CO. High fluctuations can be found in the UDC and EUDC phases. Since the NOx emission has a higher correlation with cylinder temperature, the elevated engine speed promotes the in-cylinder pressure result in higher temperature in the combustion chamber, which favors the NOx formation. The hydrogen addition results in lower fuel consumption which is gradual substitution of gasoline by hydrogen. The hydrogen addition into the intake manifold leads to lean mixture and then cause

Fig. 5. Same as Fig. 4 but for CO emissions.
lower flame temperature. This may be the reason for keeping lower cylinder temperature and effectively constrains the NOx but producing large amount of HC emissions. These obtained results are found in consistent with those reported by references (El-Kassaby et al., 2016; Jhang et al., 2016; Ji and Wang, 2010).

3.4 Accumulated Mass over Cold-Start, Idle and NEDC Driving Cycle

The accumulated mass under cold-start, idling as well as NEDC driving cycles are shown in Table 2. The cold-start and idle conditions with base fuel of G0 were 0.425 g and 0.274 g, respectively, which were around 44.9% and 30.6% over the entire NEDC driving cycle (0.945 g) (Fig. 7).

The significant reduction of HC can be found during both cold-start and idle period. The reduction rate of HC with 0.6 L min⁻¹ and 1.2 L min⁻¹ of hydrogen addition were 39.5% and 7.52% compared to conventional gasoline (G0), respectively. At idle, the effect acts similarly by decreasing 26.2% and 7.66% of HC, respectively. The emission of HC is probably related to the amount of hydrogen and some crucial radicals (OH, H, etc.). The addition of hydrogen speeds up the formation rate of OH radicals, improving the chain reaction (Shivaprasad et al., 2018). In addition, the addition of hydrogen leads no carbon atom inlet to engine. The wide flammability of hydrogen facilitates the hydrogen-gasoline mixtures to be burnt more completely under minor conditions. Similar observations were seen by references for HC emissions (Akal et al., 2020; Jhang et al., 2016; Ji et al., 2016b).

Compared to full NEDC driving cycle (3.94 g), the accumulated mass of CO under cold-start and idle conditions with base fuel of G0 were 2.27 g and 1.34 g which accounted for 57.6% and 34.0%, respectively. The decrease of CO could be observed 14.0% and 11.4% for 0.6 L min⁻¹ and 1.2 L min⁻¹
Table 2. Accumulated emission mass with hydrogen addition under cold-start, idle and NEDC driving cycle.

<table>
<thead>
<tr>
<th>Accumulated mass (g)</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NEDC</td>
<td>Cold-Start</td>
<td>Idle</td>
</tr>
<tr>
<td>Gasoline (G0)</td>
<td>0.945</td>
<td>0.425</td>
<td>0.274</td>
</tr>
<tr>
<td>0.6 L min⁻¹ of H₂</td>
<td>0.644</td>
<td>0.257</td>
<td>0.202</td>
</tr>
<tr>
<td>1.2 L min⁻¹ of H₂</td>
<td>0.818</td>
<td>0.393</td>
<td>0.253</td>
</tr>
</tbody>
</table>

![Accumulated mass of (a) HC, (b) CO and (c) NOx with hydrogen addition under engine cold-start, idle and whole driving condition (NEDC).](image)

Fig. 7. Accumulated mass of (a) HC, (b) CO and (c) NOx with hydrogen addition under engine cold-start, idle and whole driving condition (NEDC).

of hydrogen addition, respectively, compared to conventional gasoline (G0). At idle condition, the reduction for CO was also confirmed which accounted for 40.5 and 38.0% for 0.6 L min⁻¹ and 1.2 L min⁻¹, respectively. Hydrogen-gasoline dual fuel mixture increases the H/C ratio, reduces combustion duration, and improves the diffusivity of hydrogen (Hu et al., 2021). Compared to other fuels, it provides homogeneous combustion mixture and makes more oxygen to enhance the combustion. Similar results were observed in the study of Hao et al. (2016), where the author proved that CO and HC can be substantially reduced when applying hydrogen as additive fuel under cold-start condition.
The proportion of cumulative NOx emission under cold-start and idle were observed lower than those of HC and CO. The cold-start and idle with base fuel of G0 were 0.499 and 0.254 g which were 9.25% and 4.71% over the entire NEDC driving cycle, respectively. The small amount of hydrogen slightly decreased NOx by 2.2% and 0.6% for 0.6 L min⁻¹ and 1.2 L min⁻¹, respectively, since the NOx emission has a higher relationship with cylinder temperature and fuel-air mixture under cold-start condition.

Although the previous results show that NOx emissions can be reduced in terms of hydrogen addition under cold-start and the whole driving cycle. However, the cumulative mass of NOx with hydrogen addition during idle were found slightly increased in comparison with conventional gasoline (G0). The reason is that the idle duration is conducted among four UDC segments without suspension, followed by EUDC driving cycle. The increase of NOx emissions are mainly affected by cylinder temperature in the working chamber when the hydrogen blend mixture has increased. Similar research conducted by Su et al. (2018) also confirmed that the increase of hydrogen helps elevate NOx emissions during idle operation.

4 CONCLUSIONS

Hydrogen as an additive energy has been promising as alternative fuel for combustion engine since it need not required engine modification. In this study, H2 is produced by a water electrolysis and then purged into the cylinder within the intake stroke with the low rate of 0.6 and 1.2 L min⁻¹. Our results show that hydrogen addition enhances the combustion process and the average reduction rates are observed 21.6% and 65.8% for HC, 2.37% and 85.4% for CO, 7.53% and 59.3% for NOx, when run at UDC and EUDC, respectively. The cumulative mass of HC, CO and NOx show that vehicle under cold-start condition contribute the highest in comparison with idle operation. The findings of this study demonstrated that vehicle starting by less amount of hydrogen can decrease HC, CO and NOx cumulative mass. We can observe the highest fuel reduction when hydrogen serves as an additive fuel under urban driving mode (UDC). The average of fuel consumptions in operating UDC, EUDC and NEDC are decreased by 1.36%, 1.32% and 1.31%, respectively. It is noteworthy that engine cold-start conditions cause most of the pollutant emissions. Hydrogen as an additive fuel is an appropriate option for pollutant reduction which can be used to improve future energy-saving strategies.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CLD</td>
<td>Chemiluminescent Detector</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CVS</td>
<td>Constant Volume Sampler</td>
</tr>
<tr>
<td>EUDC</td>
<td>Extra-Urban Driving Cycle</td>
</tr>
<tr>
<td>FID</td>
<td>Flame Ionization Detector</td>
</tr>
<tr>
<td>G₀</td>
<td>Conventional Gasoline</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>NDIR</td>
<td>Non-Dispersive Infrared</td>
</tr>
<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>LPM</td>
<td>Liter per Minute</td>
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<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>SOₓ</td>
<td>Sulfur Oxides</td>
</tr>
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<td>UDC</td>
<td>Urban Driving Cycle</td>
</tr>
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</table>

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220259
ACKNOWLEDGEMENTS

The authors extend their immense gratitude to the National Science Council and Environmental Protection Administration of Taiwan who made this work possible under the grant NSC102-EPA-F-009-001. The authors are also equally expressing their gratefulness to the Chinese Petroleum Corporation for the support on engine test and moreover to the General Optics Corporation (GOC) who supported with the hydrogen supplied equipment that were used in this study and particularly grateful for the assistance given by Dr. Salauddin Mohammad for his intellectual support.

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