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Numerical analysis of performance and emission behavior of CI engine fueled with microalgae biodiesel blend

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ABSTRACT

The objective of current numerical analysis is to assess the compression ignition engine performance and emission indices using diesel (B0), spirulina microalgae biodiesel (SMB) blends (SMB20, SMB40, and SMB60) as fuel. The engine chosen for the experimental evaluation and tool validation is 4-stroke solo cylinder of direct injection type diesel engine cooled with water. The numerical assessment is conducted with advanced timing (23.5b TDC) of injection and nozzle opening pressure (NOP) 220 bar with half and 100% load condition. The results obtained have shown that SMB20 (20% of spirulina microalgae biodiesel and 80% base fuel) similar results to base fuel (diesel fuel). All spirulina microalgae biodiesel blends reduce brake torque (BT) by 5.7%, indicated efficiency by 0.52% and mechanical efficiency 5.5% at load full condition. Engine exhaust emission results showed that mixed fuel diminishes the oxides of nitrogen (NO_X) emission by 4.96% and smoke emission by 11.0% and enhance specific carbon dioxide (CO2) by 3.4% for SMB20 blend at full load condition. The rate of formation of soot (1/deg.) was obtained to be 1.46 for DF, SMB20 by 1.23 and SMB100 by 0.92.

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1. Introduction

The replacement of fossil fuels with sustainable and environment friendly fuels will reduce hazardous impact on environment and also fulfill the global energy requirements. Previous researchers have been reported and converted into alternative fuel of microalgae, waste plastics, Jatropha oil, waste cooking oil, turpentine, castor oil, karanja oil, mustard oil for diesel engine fuel. The alternative energy source was observed lesser pollutant emission as compared to fossil fuels [1–3].

Fuel blend mixture with various level of water contents and their encouraging influences on performance and emission indices of a CI engine are assessed. The result found that there is a rise in BTE and fall in tail pipe exhaust gas temperature (EGT) with an enhancement in water proportion in emulsion fuel. The nitrogen oxides (NOX) and smoke discharges were lower compared to base fuel but there is rise in discharge of carbon monoxide (CO) gases with blend fuel comprising of high-water proportion [4]. Poly-oxy-methylene di-methyl ethers (PODE) fuel which is having a high value of cetane number, low dynamic viscosity and high oxygen index, is identified to be a better replace for traditional diesel fuel. Results shown that diminished soot emission and elevated indicated thermal efficiency during the load sweep with blend ratio B85P15 [5]. The CI engine's novel chilling system lessens the tail pipe emissions provide better control on rate of coolant flow and temperature of engine. The increased coolant temperature and reduced coolant flow result show that reduction in exhaust gas emission but nitrogen oxides (NO_X) is higher of engine [6].

The analysis was carried out on MAB fuel blended with diesel and butanol and employed as a fuel in CI engine shown encouraging influence on performance indices and emission parameters of engine. The results depicted a slight reduction in brake torque and brake power and a rise in exhaust gas emission (CO and NOX) on addition of butanol. Therefore, butanol can be employed

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Nomenclature

b TDC	before top dead center	*ME*	mechanical efficiency
B0	0% MSS and 100% PD	*MSS*	microalgae spirulina sp.
B20	20% MSS and 80% PD	*NOP*	nozzle opening pressure
B40	40% MSS and 60% PD	NO_X	nitric oxide
B60	60% MSS and 40% PD	*PM*	particulate matter
B80	80% MSS and 20% PD	*PPM*	parts per million
B100	100% MSS and 0% PD	*PD*	petroleum diesel
BT	brake torque	*RPM*	revolution per minute
BSU	bosch smoke unit	*SFR*	soot formation rate
CO_2	carbon dioxide	*SMB*	Spirulina microalgae biodiesel
CPT	cylinder peak temperature		
DI	direct injection		
IE	indicate efficiency		

as a capable additive to diesel–MAB blends [7]. Experimental evaluation of methyl ester MAB as a fuel in compression ignition engine with different blend ratio shown similar results as that of previous case [8]. MAB has a potential for replacing diesel fuel in CI engine as a clean renewable and environmental substitute. Also, its ability to grow even in sewage water at faster rate and ability to convert CO_2 into fuel indicates its potential in the field of biofuel production [9].

The researchers investigating numerous new sources of clean energy and replacement of petroleum fuel to avoid global worming problem being faced by world. The biodiesel becomes an eco-friendly possibility to researchers for changing conventional fuel towards clean source [10]. The characteristics of biodiesel are very nearer to petroleum diesel and it can be employed in engine without any modification. But at present-day biodiesel costs nearly thrice that of diesel fuel due to the higher cost of oil crops that serves as a basis for biodiesel generation. Microalgae is the best substitute for conventional fuel and oil based biodiesel in the process of searching alternative clean energy source as it can grow faster than oil crops and can grow even in sewage water. Microalgae need much less terrestrial area than any other biofuel of agricultural source and it is identified that up to 65 times less land is needed to microalgae production than any other crops [11].

In this paper, performance and emission attributes of a CI engine is assessed using MAB and its blend (20, 40 and 60%) volume basis with diesel, at constant injection timing (23.5° b TDC) and NOP (220 bar). This experimental investigation was aimed to examine the influence of MAB on performance and exhaust of an engine at CR17.5 with 220 bar NOP and advanced injection timing at constant engine speed 1500 RPM. Here follows further instructions for authors.

2. Microalgae biodiesel

The algae biodiesel well established itself in being replacement of fossil-based fuels. Third generation classified algae biodiesel and its quality assessment as ecological fuel, making it employable in the engine [1]. MAB was well-known as substitute fuel for CI engine [12]. The properties of spirulina sp. MAB is shown in Table 1. The characteristics of MAB is the range of petroleum diesel with added advantage of less greenhouse gas emissions.

3. Experimental setup and procedure

The engine rig and conditions are shown in Fig. 1 and Table 2. The engine setup rig consists of dynamometer, CPU, fuel tank, fuel delivery control system, rotameter for engine and exhaust gas calorimeter water flow rate, load cell, exhaust gas calorimeter, exhaust gas analyzer, gate valve for emission measurement, data acquisition system (DAQ), water supply control system inlet calorimeter, exhaust and engine inlet and outlet. "A natural aspirated, single cylinder, four stroke DI CI engine was taken for the study. The engine was run with diesel fuel at no load for about 30 min with engine speed of 1500 rpm. After that, different performance parameters like efficiency, cylinder peak temperature and emission indices such as smoke level, NO_X, and CO_2 emissions, were taken at engine load. Exhaust gas emission was measured by a TESTO 350 flue gas analyzer". The technical specification of the flue gas analyzer along with gauging accuracy are shown in Table 3.

1	Engine speed	8	Fuel level indicator
2	Exhaust gas temperature sensor	9	Fuel supply to engine
3	Microalgae biodiesel temperature sensor	10	Exhaust gas calorimeter
4	Loading unit	11	Engine
5	Microalgae biodiesel	12	Eddy current dynamometer
6	Petroleum diesel	13	Computer
7	Fuel supply to fuel indicator	14	Engine bed

Table 1
Material characteristics of diesel and SMB blends.

Properties	Cetane number	Density (kg/m^3) at 15 °C	Flash point (°C)	Low heating value of fuel (MJ/kg)	Viscosity (mm^2/s) at 40 °C
Diesel fuel (B0)	48	830	76	42.5	3.62
SMB20	48.39	832.2	86.9	40.74	3.81
SMB40	49.08	839.31	97.7	39.45	3.93
SMB60	49.73	848.53	108.6	38.2	4.07
SMB100	52.0	861.0	>128.0	41.0	5.26

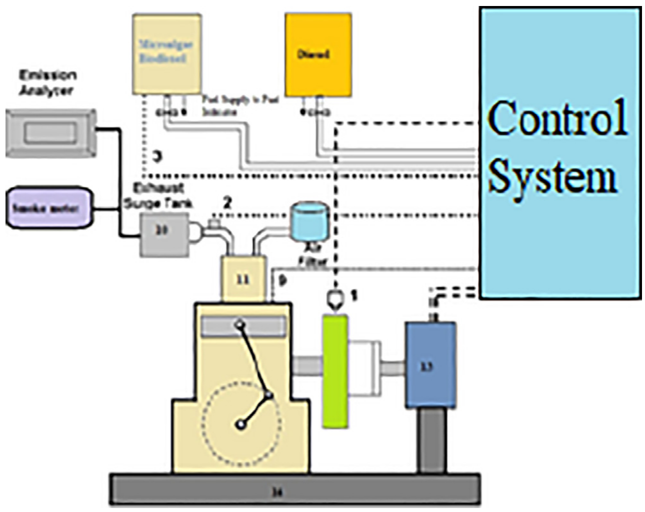

Fig. 1. Layout of engine setup.

Table 2
Engine technical specification.

Parameter	Cylinder/ stroke	Compression ration	Bore (mm) & Stroke (mm)	Speed (rpm)	Rated Power (HP)
Value	1/4	17.5:1	80 & 110	1500	3.7 kW

Table 3
Uncertainty in the setup.

Instrument	% of uncertainty
Fuel Measuring	±0.5
Load indicator	±0.2
Crank Angle encoder	±0.2
Heat value measured	±1
Pressure Sensor	±0.5
Speed transducer	±1.0
Temperature detector	±0.15
Smoke meter	±1
TESTO 350 gas analyzer	
HC	± 0.1
CO	± 0.3
CO_2	± 1
NO_X	± 0.5
O_2	± 0.3

3.1. Uncertainty analysis

The instruments percentage uncertainties of NO_X, O2, CO, HC, CO_2, smoke meter, exhaust temperature, heat value measured, load sensor etc. and were shown in Table 3. Let Uncertainty asξ

$$\begin{aligned}\%\xi = & \sqrt{\xi_T^2 + \xi_s^2 + \xi_p^2 + \xi_A^2 + \xi_f^2 + \xi_h^2 + \xi_{sm}^2 + \xi_{NOx}^2 + \xi_{CO2}^2 + \xi_{CO}^2} \\ & + \xi_{HC}^2 + \xi_{O2}^2 \\ = & \pm 2.24\%.\end{aligned}$$

4. Results and discussion

Engine combustion, performance and emission characteristics of numerical simulation was obtained of brake torque, indication efficiency, mechanical efficiency, peak cylinder temperature, specific carbon dioxide, NO_X emission, smoke level, particulate matter, soot formation rate with half and full load condition.

4.1. Engine performance parameters

Fig. 2 illustrated the variation of brake torque with engine load for DF, SMB20, SMB40, SMB60 and SMB100 blends at partial and full load. It's clear in Fig. 2, that increasing engine load improved engine brake torque and reduces with DF-SMB blends. It was observed that the brake torque reduces for the microalgae biodiesel blends due to lower calorific value and higher viscosity of fuel as compared to DF [13]. The results showed that the maximum brake torque of engine 17.96N-m for DF and 16.92N-m for SMB20 blend.

Fig. 3 shows variation of volumetric efficiency versus engine load. The effect of MSS biodiesel on volumetric efficiency and diesel fuel. It is identified the decreasing tendency of volumetric efficiency with increasing engine loading [2,3] but increasing in concentration of SMB and its blend compared to diesel fuel. The SMB biodiesel having a lower heating value compared to diesel fuel are presented in Table 1. The observed value of 92.4% for diesel fuel and 91.2% for SMB20.

Fig. 4 shows variation of mechanical efficiency versus engine load. From Fig. 4 it is identified the increasing tendency of mechanical efficiency with increase in engine loading but reducing tendency with concentration of SMB and its blend compared to diesel fuel. It is due to the lower heating value of SMB biodiesel

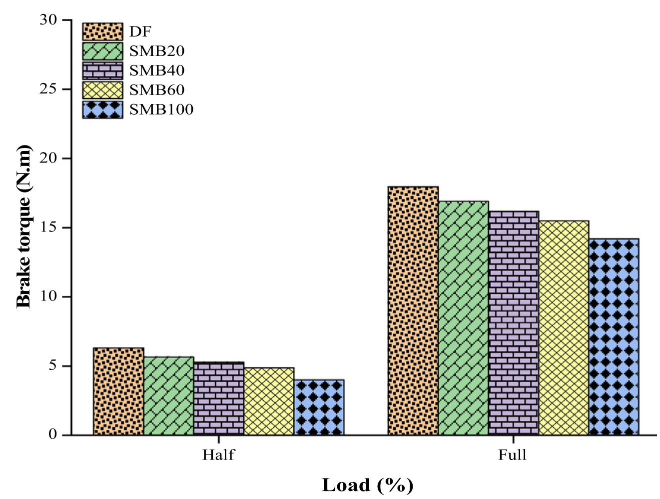

Fig.2. Variation of Brake torque versus load.

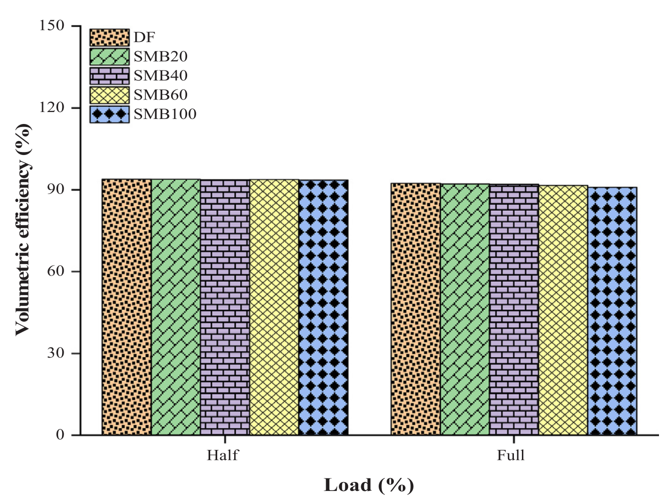

Fig. 3. Variation of volumetric efficiency versus load.

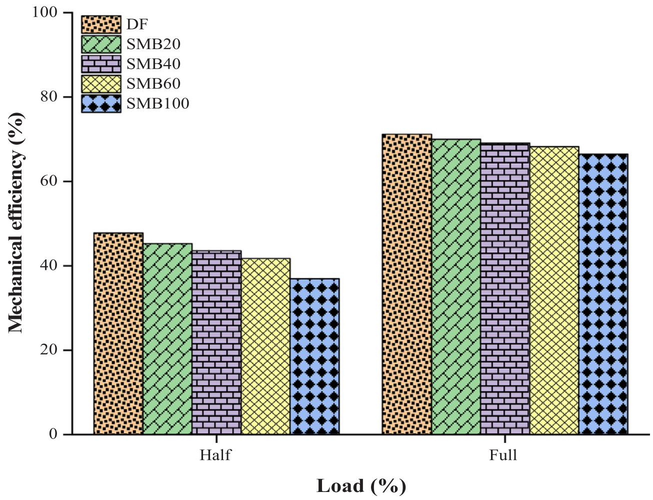

Fig. 4. Mechanical efficiency vs load.

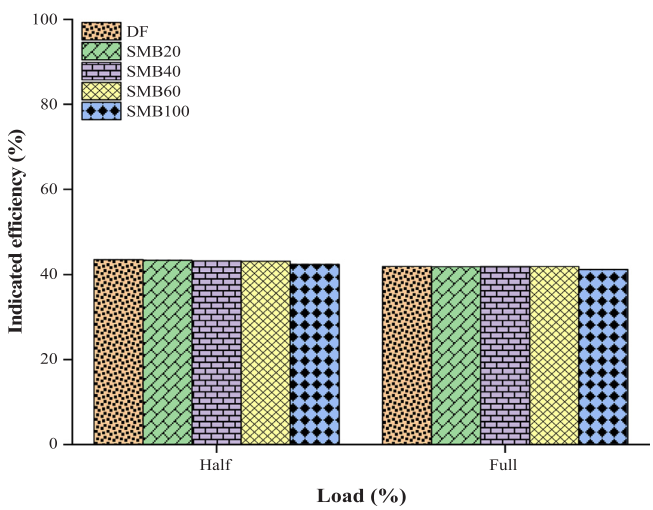

Fig. 5. Indicated efficiency vs load.

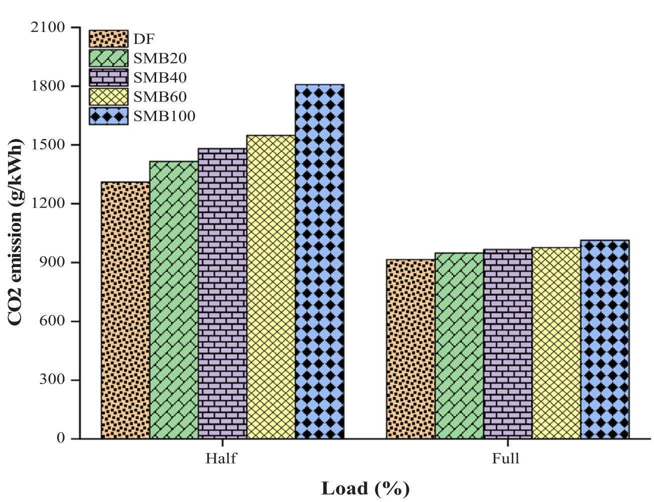

Fig. 6. CO_2 vs load.

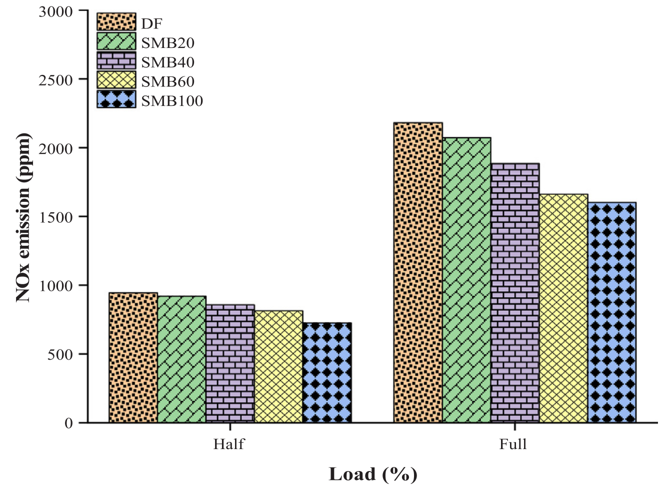

Fig. 7. Variation of NO_X versus load.

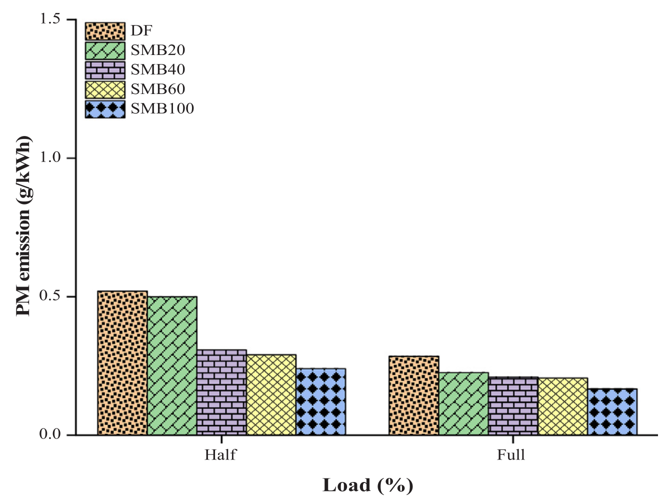

Fig. 8. PM vs load.

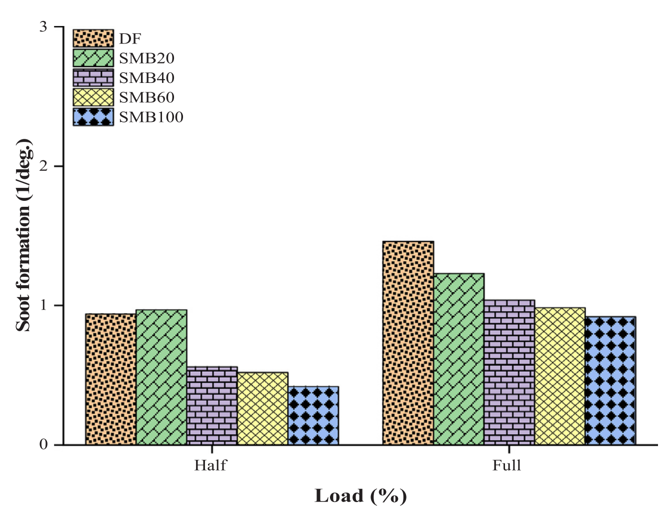

Fig. 9. SFR vs load.

compared to DF. The observed value is 71.22% for DF and 71.0% for SMB20.

The indicated efficiency changes with load for SMB and DF at partial and full load as shown in Fig. 5. The indicate efficiency is the ratio of the indicated work to input energy obtained from the engine and energy content of the fuel consumed in unit time [19,20]. It was observed that indicated efficiency was 42.1% for DF, SMB20 by 41.88% and SMB100 by 41.1%. The SMB of 20% biodiesel obtained 0.5% lower than DF due to calorific value is higher of DF.

4.2. Exhaust gas emission parameters

Fig. 6 depicts CO_2 emission change with engine load. Formation of CO_2 rises with engine load due to complete combustion. The combustion process is the key origin of CO_2 emission from diesel fuel and it is reported that the CO_2 emission is higher with percentage rise in the biodiesel. The CO_2 emission depends on O_2 presence in fuel [14,15]. The CO_2 emission of SMB20 about 948.1 g/kWh as compared to DF about 915 g/kWh. The 20% of SMB liberates 3.4% more CO_2 compared to DF at 100% load.

Fig. 7 represents NO_X emission variation with engine load. Formation of NO_X is due to rise in combustion temperature with engine load. The SMB was obtained to be lower heating value and which reduces the combustion temperature and hence NO_X emission decreased [15–18]. The AMB fuels distributed a significant reduction in NO_X emissions due to lower exhaust gas temperature [21–23]. The 5% and 26.5% reduction rates are indicated by SMB20 and SMB100 as compared to DF. The mean NO_X reduction for SMB is 18.9%.

Fig. 8 shows the change of PM emission with engine load. Formation of particulate matter (PM) is due to smoke opacity, and as load on engine increases, both PM and smoke emissions reduced. The Combustion process in chamber is the main source of PM emission from diesel fuel and reported PM emission is higher with the higher biodiesel carbon chain length. Also, PM dependent on O_2 presence in fuel [15,16]. The PM emission is lower compared to DF. The PM emission found that $0.28g/kWh$ for DF and $0.167g/kWh$ for SMB100 at 100% load.

Fig. 9 shows soot formation rate of DF, SMB and its blend with loads. Soot formation in biodiesel was lower as compared to DF due to high O_2 present in SMB. The oxygenated physical appearance of biodiesel both reduce soot formation and enhancement of soot oxidation [18]. The rate of formation of soot (1/deg.) was obtained to be 1.46 for DF, SMB20 by 1.23 and SMB100 by 0.92.

5. Conclusions

The numerical investigation of engine performance indices and exhaust parameters utilizing diesel fuel (B0) and different blends of SMB (SMB20, SMB40, SMB60 and SMB100) on a 4-stroke one-cylinder direct injection compression ignition engine cooled by water.

- MSS biodiesel is one of the alternatives to fossil fuel-based diesel, as it increases combustion phenomenon by diminishing phase to phase variation of biodiesel because of high cetane value and more O_2 content.
- Percentage rise of SMB diminished brake torque. This also shown a huge potential for reduction of CO_2 exhaust with rise in engine load.
- PM emission reduces with the rise in SMB proportion and engine load. Both BSU and SFR got diminished with the utilization of SMB.
- With rise in engine load, NO_X emissions increases but it declines with rise in SMB percentage in the blend. This is due to the better combustion process and leaner mixture.
- All SMB blends possess short ignition delay when compared to that of B0.
- It is found that tail pipe emissions of CI engine fueled with SMB are less harmful when compared to that of CI engine charged with traditional diesel fuel.
- Hence authors believe that this SMB will replace diesel fuel completely in near future to satisfy stringent global emission regulations.

CRediT authorship contribution statement

Upendra Rajak: Writing - original draft, Writing - review & editing. **Prerana Nashine:** Investigation, Methodology, Data curation, Formal analysis. **Abhishek Dasore:** Conceptualization, Data curation, Formal analysis. **Ramakrishna Balijepalli:** Conceptualization, Data curation, Formal analysis. **Prem Kumar Chaurasiya:** Data curation, Formal analysis. **Tikendra Nath Verma:** Methodology, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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