THE EVALUATION OF PREMIXED BIOGAS/AIR EXPLOSION CHARACTERISTICS IN A 20 L CLOSED VESSEL

NUR AQIDAH BINTI MUHAMMAD HARINDER KHAN

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : IR. TS. DR. SITI ZUBAIDAH BINTI SULAIMAN

Position : SENIOR LECTURER

Date :

____

(Co-supervisor's Signature)

Full Name : DR. IZIRWAN BIN IZHAB

Position : SENIOR LECTURER

Date :

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : NUR AQIDAH BINTI MUHAMMAD HARINDER KHAN

ID Number : MKG 16001

Date :

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NUR AQIDAH BINTI MUHAMMAD HARINDER KHAN

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ABSTRAK

Letupan gas yang melibatkan biogas adalah fenomenon yang serius akibat dari pembakaran pracampuran awan gas. Bagi mengkaji faktor-faktor yang menyumbang kepada kejadian letupan, kajian terperinci dan menyeluruh terhadap kepekatan bahan api, tekanan mula dan suhu, dan pencairan karbon dioksida (CO_2) telah dijalankan. Namun, kajian-kajian yang dijalankan ini hanya melibatkan campuran bahan api selain daripada biogas. Biogas merupakan gas yang mudah terbakar memandangkan komposisinya terdiri daripada 50 hingga 70% metana (CH_4), 30 hingga 50% CO_2 dan beberapa gas yang lain. Oleh itu, kekurangan data mengenai ciri-ciri asas pembakaran dan letupan biogas akan membawa kepada pertambahan potensi bahaya letupan terutamanya dalam industri. Dalam kajian ini, letupan gas di ruang terbatas telah dijalankan. Pendekatan eksperimen menggunakan bekas sfera tertutup yang mempunyai isipadu 20 L telah dipilih bagi mengkaji ciri-ciri letupan pracampur campuran biogas/udara. Faktor-faktor seperti nisbah kesetaraan (ER), kepekatan CO_2 dan tekanan mula yang menyumbang kepada ciri-ciri letupan pracampur campuran biogas/udara telah dikaji dan dianalisis melalui tekanan lebih letupan (P_{ex}), tekanan lebih letupan maksimum (P_{max}), kadar maksimum kenaikan tekanan ($(dP/dt)_{max}$) dan indeks deflagrasi gas (K_G). Berdasarkan penilaian yang dilakukan, pracampur campuran biogas/udara yang mempunyai 40% vol/vol CO_2 pada nisbah kesetaraan yang agak tinggi (ER = 1.2) adalah yang paling serius apabila meletup dengan P_{ex}, P_{max} dan $(dP/dt)_{max}$ masing-masing bernilai 8.50 bar, 9.08 bar dan 120.00 bar/ms. Selain itu, berdasarkan penilaian kepekatan CO_2, pracampur campuran biogas/udara yang mempunyai 45% vol/vol CO_2 pada ER 1.2 didapati paling tidak serius apabila meletup dengan P_{ex}, P_{max} dan $(dP/dt)_{max}$ masing-masing bernilai 7.60 bar, 8.05 bar dan 82.25 bar/ms. Ini adalah disebabkan oleh kesan fizikal CO_2 dan ketidakstabilan kemeresapan-haba. Malah, pracampur campuran biogas/udara pada tekanan mula 1.1 bar juga didapati paling serius apabila meletup dengan P_{ex}, P_{max} dan $(dP/dt)_{max}$ masing-masing bernilai 9.90 bar, 10.90 bar dan 1922.50 bar/ms. Ini adalah disebabkan oleh batasan ruang yang wujud di antara molekul, kadar tindak balas kimia yang cepat serta peranan ketidakstabilan kemeresapan-haba. Kajian ini juga menunjukkan bahawa pracampur campuran biogas/udara pada ER antara 0.8 hingga 1.5 tergolong dalam kategori kelas bahaya St-3, yakni merujuk kepada letupan yang sangat serius. Data P_{max} yang diperoleh daripada eksperimen juga telah di disahkan dengan menggunakan perisian FLame ACcelaration Simulator (FLACs). Keputusan yang diperoleh menunjukkan bahawa P_{max} yang diperoleh daripada eksperimen berada dalam lingkungan had kelainan ± 30% dan yang dianggap memuaskan. Malah, perbandingan P_{max} yang diperoleh daripada eksperimen dan data yang diterbitkan daripada kajian-kajian terdahulu juga menunjukkan trend yang setanding. Kesimpulannya, ER, kepekatan CO_2 dan tekanan awal pracampur campuran biogas/udara mempunyai kesan yang signifikan terhadap ciri-ciri letupan dan boleh membawa kepada bencana yang melibatkan letupan.

ABSTRACT

A gas explosion involving biogas is a severe phenomenon that results from the combustion of a premixed gas cloud. As of today, several explosion accidents involving biogas have been reported worldwide. Extensive and comprehensive studies have been done to investigate the factors contributing to the explosion (i.e. the fuel concentration, initial pressure and temperature, and carbon dioxide (CO_2) dilution). However, these studies have only been done involving fuel/air mixtures other than biogas. Since biogas is composed of 50 to 70% methane (CH_4), 30 to 50% CO_2 and traces of other gases, it is highly combustible. Lacked in its fundamental combustion and explosion characteristics will lead to a higher potential of explosion hazard especially in industries. In this study, a gas explosion in a confined space is considered. An experimental approach using the 20 L closed spherical vessel is adopted to investigate the explosion characteristics of the premixed biogas/air mixtures. The factors (i.e. equivalence ratio (ER), CO_2 concentration and initial pressure) contributed to the premixed biogas/air explosion characteristics (i.e. the explosion overpressure (P_{ex}), maximum explosion overpressure (P_{max}), the maximum rate of pressure rise ($(dP/dt)_{max}$) and gas deflagration index (K_G) was evaluated. From the results, it was found that the premixed biogas/air having 40% vol/vol CO_2 was the most severe when exploded at a slightly rich concentration (ER = 1.2) with P_{ex}, P_{max} and $(dP/dt)_{max}$ of 8.50 bar, 9.08 bar and 120.00 bar/ms respectively. Besides, the evaluation of CO_2 concentration in the premixed biogas/air mixture also showed that the mixture having 45% vol/vol CO_2 at ER of 1.2 was found to be the least severe when exploded with P_{ex}, P_{max} and $(dP/dt)_{max}$ of 7.60 bar, 8.05 bar and 82.25 bar/ms respectively. This was due to the physical effect of CO_2 and thermal-diffusive instability. Further, the premixed biogas/air mixture was also found to be the most severe when exploded at an initial pressure of 1.1 bar with P_{ex}, P_{max} and $(dP/dt)_{max}$ of 9.90 bar, 10.90 bar and 1922.50 bar/ms respectively. This was due to the fewer spaces between molecules, higher reaction rate as well as due to the role of thermal-diffusive instability. This study also shows that the premixed biogas/air mixture at ER ranging from 0.8 to 1.5 to fall into St-3 hazard class that was the most severe when exploded. Verification of the P_{max} obtained from the experimental results was also conducted using the FLame ACcelaration Simulator (FLACs) software. Results showed that the P_{max} was found to be within the ± 30% limit of discrepancy and is considered satisfactory. The compared P_{max} from this study with published data from literature also shows a comparable trend. As a conclusion, it shows that the ER, CO_2 concentration and the initial pressure of the premixed biogas/air mixture has a significant impact on its explosion characteristics, which can lead to a catastrophic explosion.

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LIST OF SYMBOLS

-	Negative
%	Percent
$(dP/dt)_m$	Rate of pressure rise
$(dP/dt)_{max}$	Maximum rate of pressure rise
~	Approximately
<	Less than
=	Equal
>	More than
c_p	Specific heat capacity
D	Mass diffusivity
dm^3	Cubic decimetre
ft^3	Cubic foot
g	Gram
g	Gravitational acceleration
h	Heat transfer coefficient
hr	Hour
K	Kelvin
k	Thermal conductivity
k	Turbulent kinetic energy
kg	Kilogram
kJ	Kilojoules
kPa	Kilopascal
L	Litre
l_T	Length scale
m	Meter
$\dot{m}$	Mass rate
m^3	Cubic meter
mA	Milliampere
mbar	Millibar
MJ	Megajoule
mm	Millimetre

mPa	MilliPascal
ms	Millisecond
ºC	Degree Celsius
p	Absolute pressure
P	Pressure
P_0	Initial pressure
P_{Air}	Air pressure
P_d	Expansion pressure
P_{ex}	Explosion overpressure
P_{Fuel}	Fuel pressure
P_k	Production of turbulent kinetic energy
P_m	Corrected explosion overpressure
P_{max}	Maximum explosion overpressure
psi	Pounds per square inch
P_{Total}	Total pressure
P_ε	Production of dissipation
R	Universal gas constant
R_{burned}	Radius of the burned gas mixture
Re_T	Turbulent Reynolds number
R_{flame}	Radius of the flame
R_{fuel}	Fuel reaction rate
$R_{o,i}$	Flow resistance due to sub-grid obstructions
$R_{w,i}$	Flow resistance due to the walls
R_{wall}	Radius of the vessel
s	Second
S_L	Laminar burning velocity
S_{QL}	Turbulent burning velocity in the quasi-laminar regime
t	Time
T_b	Maximum flame temperature
T_{burned}	Temperature of the burned gas mixture
T_o	Initial flame temperature
$T_{unburned}$	Temperature of the unburned gas mixture
u'	Turbulent flow

V	Volt
V	Volume
W	Molar mass
W	Watt
W_p	Inflection point
x	Length coordinate
Y_{fuel}	Mass fraction
β	Volume porosity
β	Volume porosity
β_j	Area porosity
γP	Fuel dependent parameter
ε	Dissipation of turbulent kinetic energy
ε	Rate of decay
μ	Mean velocity
μ_{eff}	Effective viscosity
ξ	Mixture fraction
ρ	Density
ρ_u	Unburned gas density
σ_{ij}	Stress Tensor
τ_c	Chemical time scales
τ_K	Kolmogorov time scale of turbulence
τ_t	Turbulent time scales
Ω	Resistance
Φ	Equivalence ratio
$\dot{Q}$	Heat rate

LIST OF ABBREVIATIONS

1D	One-dimensional
3D	Three-dimensional
A	Ampere
AD	Anaerobic digestion
Apr.	April
atm	Atmospheric
Aug.	August
BTU	British thermal unit
CDM	Clean Development Mechanism
CFD	Computational Fluid Dynamics
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CPO	Crude palm oil
Da	Damköhler number
Dec.	December
ER	Equivalence ratio
Feb.	February
FLACs	FLame ACcelaration Simulator
FS	Full scale
GHG	Greenhouse gases
GW	Gigawatts
H_2	Hydrogen
H_2O	Water vapor
H_2S	Hydrogen sulfide
H_2SO_4	Sulphuric acid
He	Helium
Jan.	January
Ka	Karlovitz number
Ka_δ	Klimov-Williams line
K_G	Deflagration index

L	Markstein length
L-D	Landau-Darrieus
Le	Lewis number
LFL	Lower flammability limit
LHV	Lower heating value
Ma	Markstein number
Mar.	March
MoSTI	Minister of Science, Technology and Innovation
N_2	Nitrogen
N_2O	Nitrous oxide
NG	Natural gas
NH_3	Ammonia
Nov.	November
O_2	Oxygen
Oct.	October
POME	Palm oil mill effluent
ppm	Parts per million
Re	Reynolds number
Sep.	September
SO_2	Sulfur dioxide
T	Temperature
UFL	Upper flammability limit
vol	Volume

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