RGC Ref. No.:
UGC/FDS24/E02/19
(please insert ref. above)

RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report

(for completed projects only)

Submission Deadlines:	*1. Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.* *2. Completion report: within **12** months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title

Develop the Most Sustainable, Safe, Reliable and Low-carbon Domestic Fuel for Hong Kong

(為香港研發最可持續性，安全，可靠及低碳的家用燃料)

2. Investigator(s) and Academic Department(s) / Unit(s) Involved

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	Professor LEUNG Chun-wah / Professor	Director's Office / School of Professional Education and Executive Development, The Hong Kong Polytechnic University (PolyU SPEED)
Co-Investigator(s)	Dr KAHANGAMAGE Udaya Priyadarshana / Senior Lecturer	Division of Science, Engineering and Health Studies (SEHS) / School of Professional Education and Executive Development, The Hong Kong Polytechnic University (PolyU SPEED)
Others	Miss NGAI Angel Tung-yan / Research Assistant	School of Professional Education and Executive Development, The Hong Kong Polytechnic University (PolyU SPEED) [Funded by this FDS Project]

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	01/01/2020	01/01/2020	08/11/2021
Project Completion Date	31/12/2021	30/06/2022	08/11/2021
Duration *(in month)*	24	30	08/11/2021
Deadline for Submission of Completion Report	31/12/2022	30/06/2023	08/11/2021

4.4 Please attach photo(s) of acknowledgement of RGC-funded facilities / equipment.

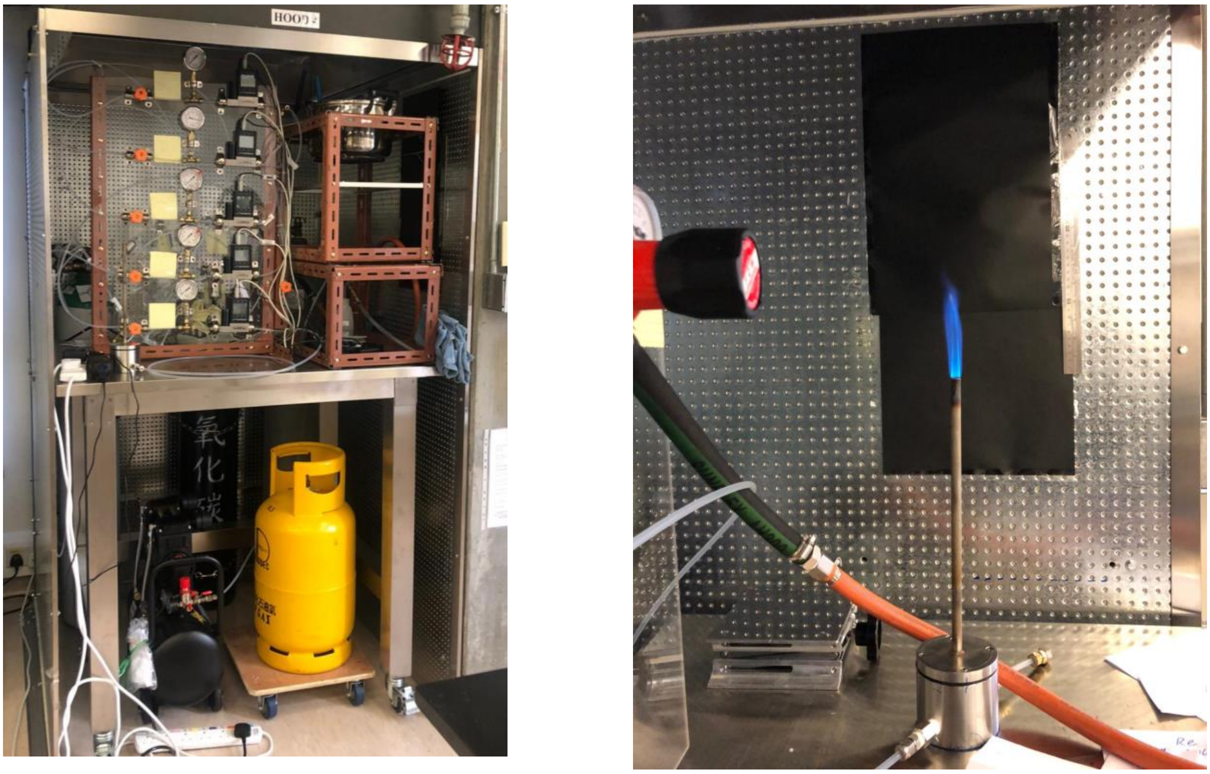

Figure 1: Test Rig for Premixed H2/LPG/Air Combustion Experiments

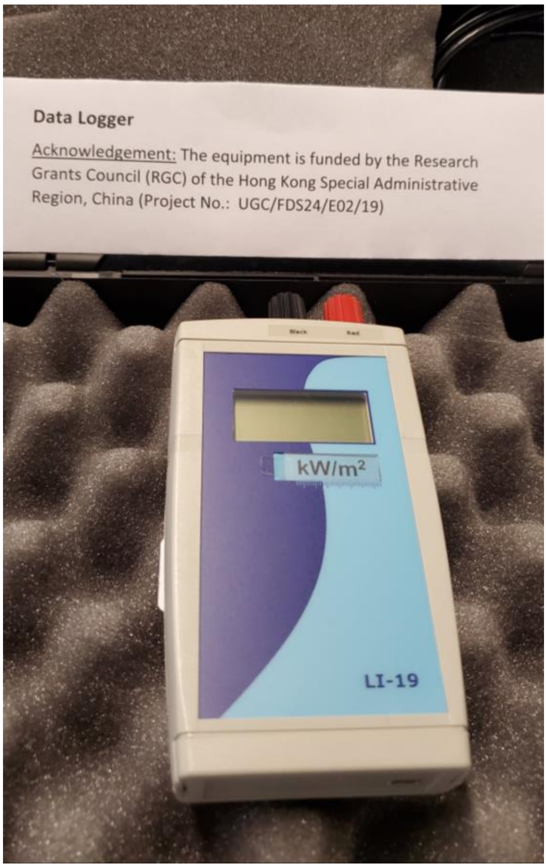

Figure 2: Data Logger

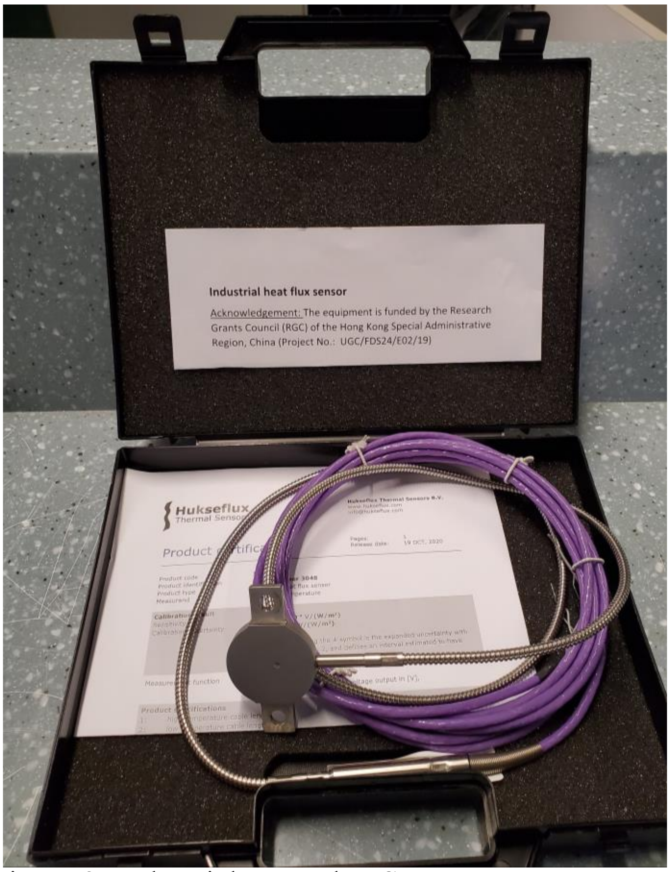

Figure 3: Industrial Heat Flux Sensor

Figure 4: Gas Sampling Rings and Standard Pots

Figure 5: Cooling Watre Syestem (Pump)

Figure 6: Cooling Water System (Chiller)

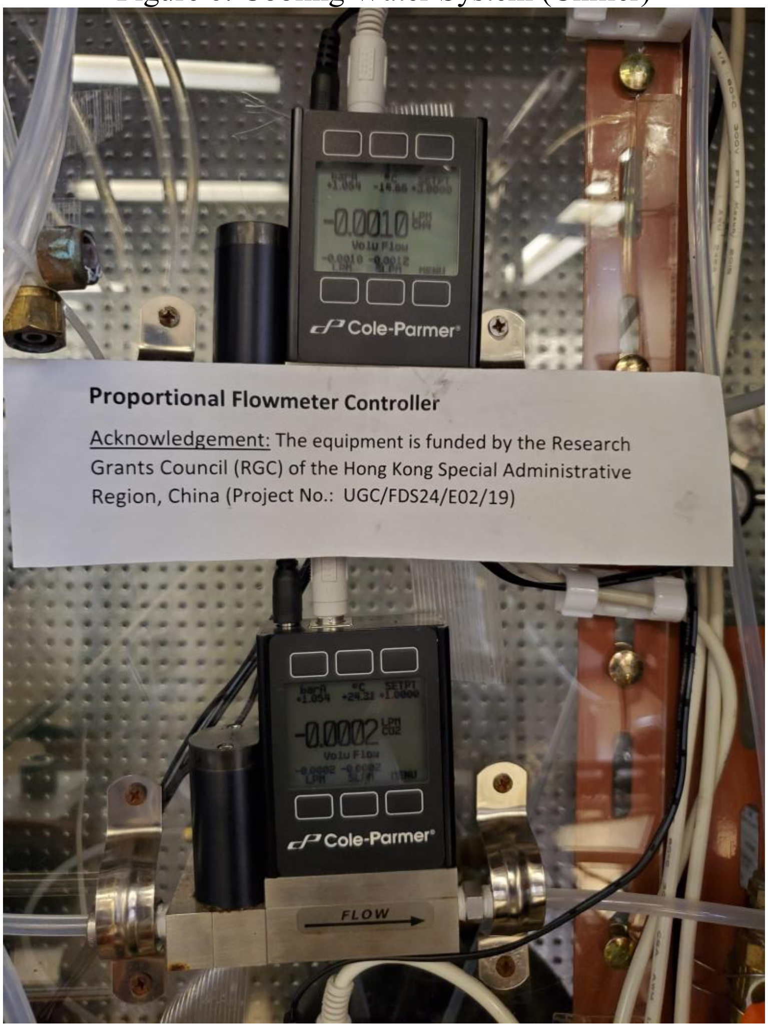

Figure 7: Test Rig Items (Proportional Flowmeter Controllers)

Figure 8: Test Rig Item (Mini Connector)

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. *To investigate the flame stability and reliability by operating within the flammability limits between the occurring of flashback and liftoff of gas-fired premixed open flame burners burning LPG blending with different percentages of H2. At a specified H2 % in the H2/LPG fuel mixture, the flame stability and flammability limits are defined in terms of the important parameters affecting the combustion process including Reynolds Number and Equivalence Ratio of the air/fuel jet, and the dominant geometrical dimensions of the burner system.*
2. *To investigate the combustion and thermal characteristics of the premixed H2/LPG/air flames (both open and impinging) including the flame shape and structure, and their hydroxyl radical (OH) generation, temperature and heat-flux distributions within the stable operation region as identified through the studies to achieve objective (1). Effects of the major parameters affecting these characteristics as mentioned under Objective (1) will be fully studied.*
3. *To investigate the emissions of gaseous pollutants of HC, CO, CO2, and NOX from the premixed H2/LPG/air impinging flame within the same stable operation ranges as identified by the investigation performed under objective (1). Effects of the major parameters affecting the formations and emissions of these gaseous pollutants as mentioned under Objective (1) will be fully explored.*
4. *It is expected that the most ideal blended H2/LPG fuel for domestic applications can be developed through the investigations performed to achieve objectives (1), (2) and (3). With the aid of the knowledge and information obtained, to design the system for producing and delivering both LPG and H2 to provide the blended H2/LPG fuel for readily use by the domestic end-users. The important design goals to achieve are safety, stability, reliability, effectiveness and user-friendliness of the fuel production and delivery systems. Problems caused by the ability of H2 to embrittle metals and the extremely low-temperature required for H2 liquification will be fully tackled. Possible problems encountered by the domestic end-users in the consequent storing and using the blended H2/LPG fuel will also be fully considered and totally solved*

5.2 Revised objectives

Date of approval from the RGC: N/A

Reasons for the change: N/A

5.3 Realisation of the objectives

(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

A test rig as shown in the Figure 1 complete with high pressure gas cylinders, air compressor, specially designed Bunsen type burner, precision flowmeter controllers, pressure gauges and data acquisition system has been developed to conduct the experimental investigations required to achieve objectives 1 – 3.

Objective 1(Fully achieved): In order to establish the stable flame region for various blends of H_2 enriched LPG, flammability limits were experimentally investigated with gas-fired premixed open flame burner. The lower flammable limits identified by occurrence of flashback were obtained for LPG-H_2 fuel blends of 0%, 5%, 10%, 15%, 20%, 25% and 30% H_2 by volume for Reynolds Number range of 600 – 1800. With the data collected a lean-burning limit map was developed for various Reynolds Numbers (600 – 1800). This map helps to identify the flame stability limits for further investigations.

Objective 2 (Fully achieved): The combustion and thermal characteristics of the premixed H_2/LPG/air flames were investigated for range of Reynolds Numbers (600 – 1800) and equivalence ratios (0.9 – 3.0) using the test rig developed. LPG-H_2 fuel blends of 0%, 5%, 10%, 15%, 20%, 25% and 30% H2 by volume were used. The flame characteristics such as flame shape, height, appearance, and flame reaction cone height were measured and analyzed. The effect of H_2 enrichment on the burning velocity was investigated numerically using ANSYS CHEMKIN. The effect of Reynolds Number and the equivalence ratio on the thermal efficiency of different blends of LPG-H_2 flames were investigated with standard water boiling test.

Objective 3 (Fully Achieved): To investigate the gaseous pollutants, flue gas samples were collected through a sampling ring placed just below the flame impinging plate. All samples were collected after maintaining stable flame conditions for at least 5mins. Multigas analyzer was used to measure CO, CO_2 and NO_x emissions. Three sample measurements were done for each test setting. With the collected data, the effects of the inter-related parameters including Reynolds Number and Equivalence Ratio of the air/fuel jet, as well as the LPG/H_2 ratio of the fuel on the pollutant-emissions were investigated.

Objective 4 (Fully Achieved): The experimental investigations performed under Objectives 1 -3 revealed that stable flame can be obtained up to H_2 enrichment of 30 vol% for the range of Reynolds Numbers (600 – 1800) and equivalence ratios (0.9 – 3.0). Interchangeability analysis with Wobbe Index calculations and experimental investigations with representative cooktop gas stove were carried out to investigate the safe, reliable and effective use of blended LPG-H_2 fuel for domestic end use. The experimental investigations were carried out according to the National Standard of the PRC for domestic gas cooking appliances (GB 16410-2020). Flame stability, pollutant emissions and thermal efficiency were investigated. The maximum safe limit of the H_2 enrichment that can be practically used with existing LPG gas stoves without any physical modifications has been established by investigating thermal efficiency, flashback potential, and pollutant emissions. The directions for further research on enhancing the safety and reliability in fuel blending, storing and delivery are also identified.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. To investigate the flame stability and reliability by operating within the flammability limits between the occurring of flashback and liftoff of gas-fired premixed open flame burners burning LPG blending with different percentages of H_2. At a specified H_2 % in the H_2/LPG fuel mixture, the flame stability and flammability limits are defined in terms of the important parameters affecting the combustion process including Reynolds Number and Equivalence Ratio of the air/fuel jet, and the dominant geometrical dimensions of the burner system.	√	100%
2. To investigate the combustion and thermal characteristics of the premixed H_2/LPG/air flames (both open and impinging) including the flame shape and structure, and their hydroxyl radical (OH) generation, temperature and heat-flux distributions within the stable operation region as identified through the studies to achieve objective (1). Effects of the major parameters affecting these characteristics as mentioned under Objective (1) will be fully studied.	√	100%
3. To investigate the emissions of gaseous pollutants of HC, CO, CO2, and NOX from the premixed H_2/LPG/air impinging flame within the same stable operation ranges as identified by the investigation performed under objective (1). Effects of the major parameters affecting the formations and emissions of these gaseous pollutants as mentioned under Objective (1) will be fully explored.	√	100%
4. It is expected that the most ideal blended H_2/LPG fuel for domestic applications can be developed through the investigations performed to achieve objectives (1), (2) and (3). With the aid of the knowledge and information obtained, to design the system for producing and delivering both LPG and H2 to provide the blended H_2/LPG fuel for readily use by the domestic end-users. The important design goals to achieve are safety, stability, reliability, effectiveness and user-friendliness of the fuel production and delivery systems. Problems caused by the ability of H_2 to embrittle metals and the extremely low-temperature required for H_2 liquification will be fully tackled. Possible problems encountered by the domestic end-users in the consequent storing and using the blended H_2/LPG fuel will also be fully considered and totally solved	√	100%

6. Research Outcome

6.1 Major findings and research outcome
(Maximum 1 page; please make reference to Part C where necessary)

This research study involves the use of LPG blended with hydrogen which is a highly flammable, potentially explosive and light gas. Therefore, the experimental work was started by performing a parametric and safety study. This study was performed using blended biogas/hydrogen fuel which is proven to be a safe blend of fuel. The findings from this study helped to establish the safe limits of hydrogen enrichment within the equivalence ratio range of 1.0 – 3.0 and Reynolds Number range of 300 – 1500 (covering entire laminar flow region). It is found that stable combustion can be ensured up to the hydrogen enrichment of 30% by volume without any unusual combustion behavior. Beyond this limit, it was observed some instability of flame, a significant formation of NO_x and significant rise in flame temperature (journal publications 1 and 2: C(8)).

Numerical investigations with ANSYS CHEMKIN were performed to study the Laminar Burning Velocity (LBV) of various LPG-H_2 blends for range of equivalence ratios. The results showed that the LBV increased with the increment of H_2 fraction and it may adversely affect the flashback potential for fuel mixture with high percentage of H_2. Through the experimental investigations conducted, the flammability limits (lean-burning limits) of LPG-H_2 blends with H_2 volume fraction of 0%, 5%, 10%, 15%, 20% and 25% were established for the Reynold Numbers ranging from 600 – 1800. Experimental results mostly agreed with the numerical predictions. The results showed that the lean-burning limit is increased, on average, by 4.0% to 7.2% for every 5% increment of H_2 volumetric fraction under different Reynolds numbers. It is due to the higher burning velocity of H_2 rich mixtures. A lean-burning limit map was developed for H_2 enrichment range from 0% - 25% and Reynolds Number range from 600 – 1800 (journal publication 3: C(8), training students: C(10)).

From the combustion and thermal characteristics investigations of premixed flames, it was found that overall flame shapes and the characteristics remain almost the same for pure LPG and LPG-H_2 blends up to 25% H_2 (highest H_2 concentration tested). This observation supports the contention that there is a good blending of the LPG and H_2 in the fuel jet, even though the physical properties of LPG and H_2 are quite different. However, the measurement of flame cone height showed that the cone height reduces with the increment of H_2 fraction. It is due to the high burning velocity of H_2 rich mixtures. Thermal efficiency measurements showed that the efficiency reduces with the increment of the H_2 fraction. It is due to the low volumetric heating value of H_2 compared with LPG. Thermal efficiency reduced further with the increasing Reynolds number for all equivalence ratios tested (journal publication 3: C(8), conference presentation: C(9), training students: C(10)).

The emissions investigations performed showed a general reduction of CO_2 and CO emissions within the range of equivalence ratio and Reynolds Numbers as the hydrogen fraction increased. It is due to the reduction in the carbon content in the fuel blend and the enhancement of combustion efficiency by H_2 with high LBV and adiabatic flame temperature. The H_2 addition, however, negatively affected the formation of NO_x. NO_x formation gradually increased with increment of H_2 fraction due to temperature effect. High flame temperature of H_2 rich mixtures enhanced the NO_x formation (conference presentation: C(9), publication 4 (under preparation): C(8), training students : C(10)).

The interchangeability analysis revealed that the maximum potential H_2 enrichment is limited to 15 vol% considering the heat input needs of domestic cooktop burners. The experimental investigations carried out according to GB 16410-2020, showed that a typical LPG cooktop stove (self-aspirating type) can be operated with LPG-H_2 blends with up to 15 vol% H_2 safely without any physical modifications. No significant changes to the emissions and the flame stability were observed (publication 4 (under preparation): C(8), training students : C(10)).

6.2 Potential for further development of the research and the proposed course of action *(Maximum half a page)*

Through this research project, we have enhanced our knowledge base on fundamental combustion, thermal and emission characteristics of different blends of H_2 enriched LPG. The practical limits of gas interchangeability with existing designs of LPG cooktop gas stoves have also been established. However, there are some instabilities observed at the ignition and during extinction of the flame that may affect the operational safety of the appliances. With the use of knowledge generated, there is a potential for further development of the research to investigate the reasons for flame instabilities and explore the maximum H_2 enrichment limits tolerable for range of appliances commonly used in domestic sector without significant effect on the appliances and combustion performance while meeting safety requirements. Identification of the design parameters of the burner head that causes the flashback risk will lay the foundation for development of burners to operate with H_2 rich fuel blends.

For the proposed investigation, a numerical model of the combustion within the burner cavity should be developed. The combustion, thermal and emission data gathered in this project can be used for the development of numerical model. With the use of the numerical model, the effect of burner port dimensions, cavity configuration, injector dimensions, etc. can be investigated to decide the best design parameters. Experimental investigations can be carried out with new designs of burners to validate the numerical results to build a better predictive model.

7. Layman's Summary

(Describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

Currently, domestic energy needs are mostly satisfied through hydrocarbon fuels. To reduce the environmental impact from domestic energy use, options for decarbonization of domestic fuels should be explored. In this study, the potential of using H_2 enriched LPG as an alternative greener fuel has been explored. Combustion, thermal and emission characteristics of different blends of LPG-H_2 have been investigated. The H_2 enrichment enhanced the laminar burning velocity of the fuel blends and hence altered the flammability limits. There is also a reduction in thermal efficiency and emission of CO and CO_2. It was found that a stable flame can be obtained up to the H_2 enrichment of 30 vol% with premixed flame. For H_2 rich mixtures, there is a significant reduction in thermal efficiency, increase in NO_x emissions and difficult to maintain stable flame. Based on the experimental results, a Lean-burning limit map has been developed. The combustion, thermal and emission data gathered in this study lay the foundation for further research in developing LPG-H_2 blended fuel for domestic use. The gas interchangeability analysis and the experiments performed show that the LPG-H_2 blends with up to 15 vol% H_2 can readily be used safely with existing designs of LPG cooktop burners without any physical modifications.

Part C: Research Output

8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications									
Year of Publication	**Year of Acceptance** *(For paper accepted but not yet published)*	**Under Review**	**Under Preparation** *(optional)*	**Author(s)** *(denote the corresponding author with an asterisk*)*	**Title and Journal / Book** *(with the volume, pages and other necessary publishing details specified)*	**Submitted to RGC** *(indicate the year ending of the relevant progress report)*	**Attached to this Report** *(Yes or No)*	**Acknowledged the Support of RGC** *(Yes or No)*	**Accessible from the Institutional Repository** *(Yes or No)*
2021	-	-	-	Chen, Y., Kahangamage, U., Zhou, Q., and Leung, C.W*.	Chen, Y., Kahangamage, U., Zhou, Q., & Leung, C. W. (2021). Can hydrogen enriched biogas be used as domestic fuel?-part i – thermal characteristics of blended biogas/h2 impinging flames. HKIE Transactions Hong Kong Institution of Engineers, 28(2), 60-67. https://doi.org/10.33430/v28n2thie-2020-0040	2020	Yes [Full Paper: Appendix 1]	Yes	Yes
2021	-	-	-	Kahangamage, U. *, Chen, Y., Zhou, Q., and Leung, C.W.	Kahangamage, U., Chen, Y., Zhou, Q., & Leung, C. W. (2021). Can hydrogen enriched biogas be used as domestic fuel?-part ii: Pollutants emission from combustion of biogas/h2/air fuel mixture. HKIE Transactions Hong Kong Institution of Engineers, 28(2), 68-74. https://doi.org/10.33430/v28n2thie-2020-0042	2020	Yes [Full Paper: Appendix 2]	Yes	Yes

The Latest Status of Publications				Author(s) *(denote the correspond-ing author with an asterisk*)*	Title and Journal / Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowl-edged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
Year of Publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2022	-	-	-	Udaya Kahangamage*, Yi Chen, Chun Wah Leung, Tung Yan Ngai	Kahangamage, U., Chen, Y., Leung, C. W., & Ngai, T. Y. (2022). Experimental Study of Lean-burning Limits of Hydrogen-enriched LPG Intended for Domestic Use. Journal of Energy and Power Technology, 4(2). https://doi.org/10.21926/jept.2202016	No	Yes [Full Paper: Appendix 3]	Yes	Yes
			√	Udaya Kahangamage*, Chun Wah Leung, Tung Yan Ngai	Hydrogen-enriched LPG as a Domestic Fuel: Interchangeability Analysis and Experimental Study of Combustion Performance of a Cooktop Burner (Proposed Journal: Fuel)	No	Yes [Abstract: Appendix 4]	Yes	-

9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered

(Please attach a copy of each conference abstract)

Month / Year / Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowledged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
Dec/2022/ Hong Kong	Hydrogen-enriched LPG: Towards Decarbonisation of Domestic Fuel	Regional Conference on Green Technologies and Sustainable Development 2022	-	Yes [Abstract: Appendix 5]	Yes	Yes

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning

(Please elaborate)

This research experience has contributed in providing better laboratory teaching and related Capstone Project learning experience for Mechanical Engineering undergraduate students. Some research experinnce have also provided to selected undergraduate students by involving them as student helpers of this project.

Making use of the research experience and the facilities developed for experimental investigations, several related Capstone Projects were developed for Final Year Mechanical Engineering students. Some of the projects have been completed and a rich learning experience in terms of related knowledge and experimental investigation methods, data analysis and academic writing were provided to students. Following is a list of completed and ongoing Capstone Projects arising from this research experience:

1. Thermal and combustion characteristics of the premixed hydrogen/biogas flame (completed)
2. Development of sustainable domestic fuel: LPG/biogas (completed)
3. Investigation of the premixed blended hydrogen/LPG fuel (completed)
4. Development of sustainable domestic fuel: blended LPG/biogas (completed)
5. Biogas for Domestic Heating (ongoing)
6. Numerical Investigation of Combustion Characteristics of Hydrogen-enriched Low to Medium Calorific Value Landfill Gas (ongoing)

The technical staff involved in the laboratory operations have also got good learning experience through the involvement in design, fabrication, operation and maintenance of the test rig and related equipment. This learning experience helps them to provide better support for laboratory learning activities of subjects ‘Engineering Thermodynamics’ and ‘Heat and Mass Transfer’ offered to undergraduate students. The technical and teaching staff are now more capable of providing necessary technical/learning support and supervision for students undertaking related Final Year Capstone projects.

Selected final year Mechanical Engineering undergraduate students were involved in this project as student helpers to carryout selected parts of the project under the supervision of the investigators and the research assistant. The PolyU SPEED’s standard recruitment procedure of recruiting part-time student helpers was applied in selecting and appointing the student helpers. They were trained in systematic literature review and academic writing, design and fabrication of test rigs for experimentations, carryout experiments by following standard procedures, systematic data collection and data interpretation & analysis.

11. Student(s) Trained
(Please attach a copy of the title page of the thesis)

Name	Degree Registered for	Date of Registration	Date of Thesis Submission / Graduation
N/A	N/A	N/A	N/A

12. Other Impact
(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

1. *Establishment of Collaboration with the Flame and Combustion Laboratory of Hainan University, China*

During this project, Investigators managed to establish contacts with researchers attached to the Flame and Combustion Laboratory at the Mechanical and Electrical Engineering College, Hainan University, China. Technical expertise has been exchanged during the design and construction of the test rig for this project. This collaboration helped us to enhance mutual understanding of our research directions and establish framework for collaborative research. One of the key outcomes is the development of a collaborative research project which was ultimately funded by RGC under Faculty Development Scheme (FDS) 2022/23 (Project Title: "Numerical and Experimental Investigation of the Combustion and Emission Characteristics of Low to Medium Calorific Value Landfill Gas Blended with Hydrogen", RGC Ref. No.: UGC/FDS24/E11/22). One of the Co-Investigators of this research project is from Hainan University and the laboratory support is provided by the Flame and Combustion Laboratory of Hainan University. The same collaboration has lead into the development of another research proposal which was submitted for RGC FDS Funding Scheme 2023/24.

2. *Teaching Enhancement*

The experience gained, equipment acquired and the physical laboratory facilities developed under this project enhanced the laboratory teaching of subjects 'Engineering Thermodynamics' and 'Heat and Mass Transfer' at Poly SPEED. It also facilitated many related Final Year Capstone Projects as outlined in **Section 10**.

13. Statistics on Research Outputs

	Peer-reviewed Journal Publications	Conference Papers	Scholarly Books, Monographs and Chapters	Patents Awarded	Other Research Outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	3 (Published) 1 (Under Preparation)	1	0	0	-	-

14. Public Access Of Completion Report

(Please specify the information, if any, that cannot be provided for public access and give the reasons.)

Information that Cannot Be Provided for Public Access	Reasons
N/A	N/A