ENHANCING KNOWLEDGE OF ENGINEERING STUDENTS AT ALL LEVELS ON ORGANIC RANKINE CYCLE SYSTEMS FOR THEIR APPLICATION IN THE BUILT ENVIRONMENT

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ABSTRACT

According to IEA, the global energy crisis is accelerating the use of renewable energy in the next five years. Furthermore, the building sector which accounts for about 30% of the final energy consumption, has a significant room of improvement in curbing its share and integrating renewable energy technologies. Hence, the co-funded 'Skybelt' project by the EU under the framework of the Erasmus+ programme coordinated by eCampus University, Italy, aims at enhancing the skills of engineering students at all levels for application of sustainable renewable energy solutions to be integrated into the built environment in several Asian and European universities.
The market analyses conducted in the initial stage of the project have revealed that combined heating and power (CHP) and combined cooling, heating, and power (CCHP) are the most interesting kinds of application of knowledge of future employees on renewable energy. Organic Rankine cycle (ORC) systems are interesting for building energy sector thanks to their capability to be combined with solar and biomass sources.
Therefore, University Putra Malaysia (UPM), University Sains Malaysia (USM) and Naresuan University (NU) opted to be equipped with non-regenerative ORC test benches for training of engineering students at different levels. In particular, bachelor students at UPM will work on the development of different control approaches on small-scale ORC units within the modernised module of 'Control Analysis System', and students at USM and NU will be trained on the operating performance of these systems to be combined with different renewable energy sources. Hence, the project has been the opportunity to foster the knowledge about the ORC systems for engineering students at all levels with the perspective of adopting them in buildings.

1 INTRODUCTION

Buildings are the single largest energy consumer in EU accounting for approximately 40% of the EU energy consumption and 36% of greenhouse gas emissions (European Commission, 2021). In particular, 27% of final energy consumption in 2020 was accounted for households according to Eurostat (2022), of which 62.8% for space heating, 15% for water heating and 0.4% for space cooling that is accelerating faster. Despite these numbers may differ in other regions of the world, the high impact of the building sector in the energy consumption is significant as in Asia and its South East. Furthermore, in the transition towards a more secure and sustainable energy supply, renewable power

additions must triple (825 GW of renewables each year until 2050) to reach the average milestones set by the IEA's Net Zero scenario by 2050, and by the World Energy Transitions Outlook scenarios from the IRENA (REN21, 2022).
Such a challenging commitment requires a competent workforce of practitioners and professionals with strong knowledge in renewable energy technologies (RETs). In the recent years, the labour market has been pulled by an increasing demand of employment linked to RETs. Fragkos and Paroussos (2018) by investigating the net employment impacts of the EU energy sector transformation towards a renewable energy one, found that this low-carbon transition would reallocate about 1.3% of the EU's workforce across sectors by 2050. Hence, educational curricula incorporating themes related to renewable energy and sustainable livelihood is required to be considered in the academic education to deliver trained alumni for such transition.
Educating green collar workers to develop and promote renewable energy technologies with technical, professional, and managerial abilities for renewable and sustainable energy sector is among the missions of many universities programmes worldwide and strongly promoted by the EU. In this context, the 'Skybelt' project (2020), co-funded by EU under the framework of the European Union's Erasmus + programme and coordinated by the University eCampus, Italy, aims at enhancing the skills of engineering students at all levels for application of sustainable renewable energy solutions to be integrated into the built environment in several Asian and European universities. All these universities are experiencing an increasing interest in offering up to date and advanced courses on RETs with special focus on those to be integrated in the building energy sector. Among the possible renewable energy conversion technologies, organic Rankine cycle (ORC) systems have attracted attention thanks to their capability to be combined with geothermal, solar, and biomass sources. Therefore, in the context of the project three Asian universities opted to equip their laboratories with non-regenerative ORC test benches for training of their engineering students at different levels.

2 THE SKYBELT PROJECT

The Skybelt project is a cooperation between 3 EU universities in Italy, United Kingdom, and Turkey, and 6 Asian universities in China, Malaysia, and Thailand. More precisely, eCampus University, Northumbria University and Cukurova University from EU countries, Beijing University of Technology, and Lanzhou Jiaotong University from China, University Putra Malaysia (UPM), University of Sains Malaysia (USM) from Malaysia, and Chiang Mai University and Naresuan University (NU) from Thailand.
The modernized teaching methods and contents to be implemented in the 'Skybelt' project were designed based on a student-centred approach having at its focus the satisfaction of the current and future market needs. In this perspective, relevant stakeholders and organisations were interviewed in the early stage of the project to provide feedback on the kind of knowledge and expertise the future engineers should have. More than 120 organisations were identified in Partner Countries of the project and about 110 interviewed. Among the relevant results obtained from this survey some are following and further details on the results of this analysis can be found in (Cioccolanti et al., 2021).

- efficiency improvements and reliability and durability of RETs are considered the main challenges to be faced;
- solar energy and heat pumps are considered the main required topics of knowledge of future employees on RETs;
- great interests were expressed for combined heating and power (CHP), and combined cooling, heating, and power (CCHP) ;
- 11.4% of the interviewed organisations considered ORC technology of interest;
- control and automation, data analysis, and predictive control are the most demanded expertise for future employees.

The outcomes of this survey have driven the selection of modules to be modernized or introduced as new in Partner Countries universities together with the teaching content and methods. Being ORC technology and CHP applications of interest for many stakeholders, UPM, USM, and NU decided to include the study of ORC systems in the content of some modules and equip their laboratories with a test bench to train their students in this field.

3 THE ORC TEST BENCHES AND THEIR USE

In this section, the driving aspects in the design of the required ORC system test benches and their use at different Asian universities are discussed.
Considering the budget constraints and the application, subcritical and non-regenerative ORC systems have been considered in all the three cases. Heat is provided using diathermic oil circuit heated by electrical heaters to replicate low temperature applications such as in the case of traditional solar thermal technologies (solar panels and evacuated tubes). Water is used as cooling medium and its heat discharged to the ambient using a chiller
. As regards the expansion device, scroll compressor converted to expander was selected being a common device in many micro-scale ORC systems.
The main characteristics of the ORC test benches in each Asian university are reported together with the kind of analysis to be performed by students within the modernised curricula in the following.

3.1 University Putra Malaysia

At University Putra Malaysia, the experimental test rig has been installed at the premises of the Department of Aerospace Engineering as shown in Figure 1. It consists of the following main components: (i) 500 W scroll expander; (ii) 10 kW electric heater; (iii) plate heat exchanger evaporator and condenser; (iv) 370 W pump. Silicone oil is used to transfer heat generated by the electric heaters to the working fluid (R134a).
The system has been designed to operate with a nominal evaporation temperature of the working fluid equal to 80°C with a maximum superheating temperature up to 100°C. The condenser temperature for the ORC operation is 20-50°C using the cooling water circuit.

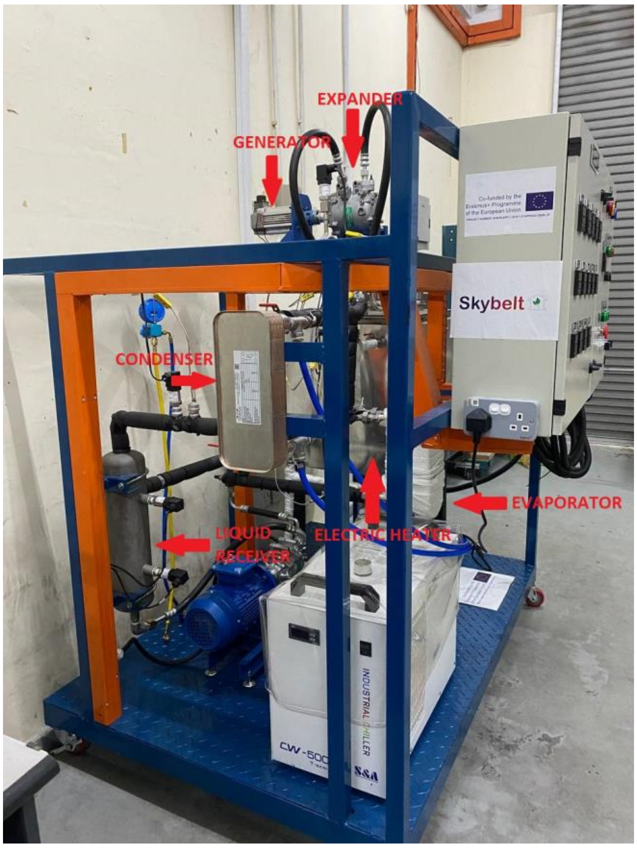

Figure 1: Experimental test rig at the premises of University Putra Malaysia

The students are required to demonstrate and obtain the amount of electric power produced by the ORC unit with varying heat source temperature. At the end students are able to correlate the performance of the ORC system in terms of expander power output with the heat source temperature and thermal power input. The procedure for this experiment is as follows:

1. Set the oil inlet temperature to evaporator to 40°C;
2. Set the oil pump frequency to 40 Hz and turn on the pump;
3. Set the refrigerant pump frequency to 50 Hz;
4. Wait for the stabilization of the operating conditions (i.e., the expander inlet temperature and pressure, refrigerant mass flow rate);
5. Check if the evaporator pressure is at the setting value (1-2 bar);
6. Check if the evaporator temperature is lower than the superheated value. If this is the case, then increase the oil inlet temperature;
7. Verify the expander shaft speed. If the speed is too high, then increase the electrical load;
8. Increase the temperature of the heater slowly with a step of 5°C until it reaches 90°C;
9. The ORC starts to operate when all the critical setting of parameters (Step 1 to 8) are fulfilled. The scroll expander starts rotating and the power output is measured at the load bank.

Within the modernised module of 'Control Analysis System', bachelor students at UPM are going to develop real time measurement system for the pressure and temperature of the working fluid at the inlet and outlet of the main components. The LabVIEW software and NI Compact DAQ 9174 chassis will be used to monitor these parameters. The NI 9203 analogue input module will be used to measure the input current from the pressure transducers and the NI 9211 temperature input module will be used to measure the temperature from the thermocouples. The hardware is shown in Figure 2a. For the pressure measurements, students will calibrate the sensors using the LabVIEW software by converting the measured current to pressure such as shown in Figure 2b.

a) b)

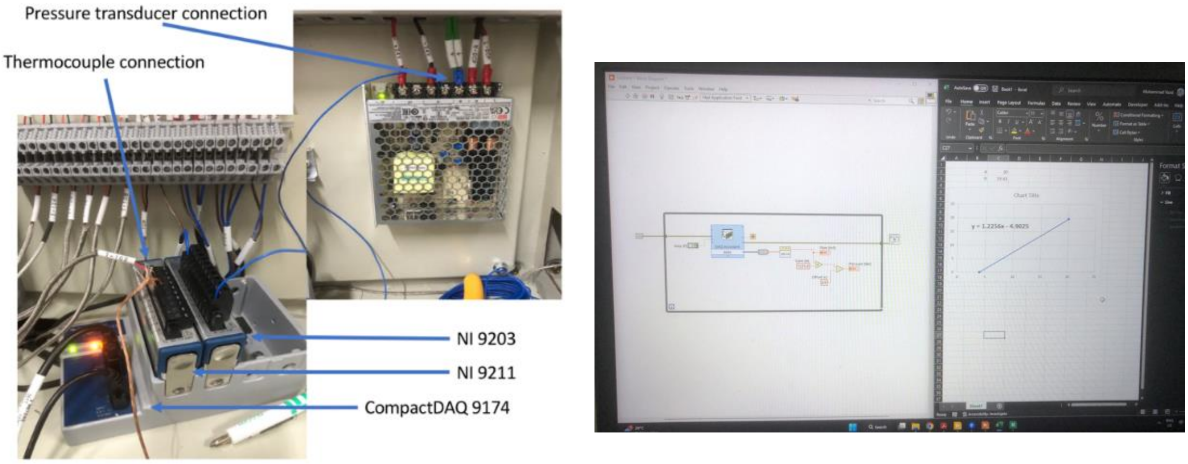

Figure 2: a) Hardware for the data measurement system; b) LabVIEW program for calibration of the pressure measurement

Furthermore, a more complex experiment will be proposed for the final year project by expanding the function of the data acquisition system. Students will be able to perform a parametric study by changing the variables affecting the outputs of the ORC and devise a controller for the ORC system to obtain optimal control of the expander power output.

3.2 University Sains Malaysia

At University Sains Malaysia, the ORC test bench is installed at the Advanced Renewable Energy Laboratory of the Science and Engineering Research Centre (SERC) as shown in Figure 3. The characteristics of the test bench are the same as the one installed at UPM.

The performance of the ORC unit is assessed in terms of power produced by the expander by changing the electrical load. During the experiments, students can analyse the critical operating parameters such as the evaporation temperature and pressure and the condensing temperature with varying heat source power input and temperature. Furthermore, students can test different working fluids and analyse their impact on the system performance.

(a) (b)

<u>Note:</u>

1. Water Cooler Chiller
2. Condenser
3. Pump
4. Expander
5. Generator
6. Liquid Receiver
7. Evaporator
8. Finned Tube Heat Exchanger Tank
9. Control Panel Box
10. Oil Pump
11. Indicators of Temperature and Pressure
12. Control Panel with Switches

Figure 3: Experimental test rig at the premises of University Sains Malaysia (a) ORC piping and connection, (b) Control panel with switches and indicators of temperature and pressure.

Within the selected modernised modules of Internal Combustion Engine and Open-ended laboratory, students will be trained to operate the ORC system based on the following experimental procedure:

1. Ensure all the system components are in good condition and the connection of the main power supply is intact.
2. Turn on the main switch and make sure the main power board and displays are functional.
3. Turn on the chiller and set the cooling water temperature at 5°C. Record the reduction of condenser temperature at the interval of 5–10°C until the temperature reaches the setting value.
4. Turn on the heater switch and set the oil temperature at 80°C. Record the increment of oil temperature at the interval of 5-10°C until the temperature reaches the setting value.
5. Set the oil pump (Pump 1) frequency to 30 Hz and turn on the pump.
6. Set the refrigerant pump (Pump 2) frequency to 20 Hz.
7. The ORC starts to operate when all the critical setting of parameters (Step 1 to 7) are fulfilled. The scroll expander starts rotating and the power output is measured at the load bank.

This experimental procedure can be repeated for different types of working fluids for low-temperature applications.

3.3 Naresuan University

At Naresuan University the operating demonstration of low grade heat can be recovered into useful electric power using Organic Rankine Cycle is performed through a TH12 model test bench installed at Department of Mechanical Engineering, Faculty of Engineering. The apparatus is designed to support the teaching of ORC systems at different levels: i) undergraduate students in mechanical engineering will be trained on the operating characteristic of ORC systems; ii) postgraduate students will benefit from the modernised courses of the master course in mechanical engineering and understand the capability of ORC systems in exploiting low-temperature renewable heat sources; and iii) PhD students will conduct experimental investigations using the comprehensive measurement devices and data logging systems. R134a is charged in this small system shown in Figure 4, which is composed of a 500 W scroll compressor converted to an expander, coil heat exchangers for the evaporator and the condenser, and a canned motor centrifugal pump. The low-temperature heat from renewables is simulated by 12 kW electrical heaters heating diathermic oil circuit, and water is used as cooling medium at the condenser. In turn, an air cooled chiller is used to cool down the water.

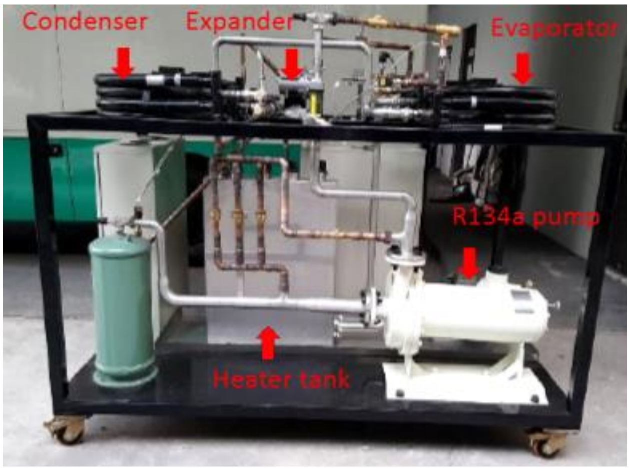

Figure 4: ORC test rig installed at Naresuan University

The system is designed to operate with nominal evaporation and condensing temperatures of 80°C and 46°C respectively. Coil condenser is cooled using chilled water. The hermetic scroll expander is connected to a brushless generator with permanent magnets having a maximum DC power of 1500 W at 6000 rpm, high voltage from 200 to 350 V and DC low voltage from 9 to 16 V. Both scroll expander and generator are inside a sealed casing with shell strength being 8.3 MPa on the high pressure side and 5.2 MPa on the low pressure side.

Pressure transducers with the operating range of 0-40 bar and safety pressure switch are installed at the evaporator inlet and outlet points. Pressure sensors with the range of 0-25 bar are installed at condenser inlet and outlet points. Eight thermocouples for measuring temperature of refrigerant, oil, and water are placed at inlet and outlets of condenser and evaporator. A PLC data acquisition and control with LCD touch screen displays operating parameters as shown in Figure 5, i.e. pressure, temperature, and flow rate of the fluids together with the power output of the expander. Data acquisition software is written in LabVIEW and all acquired data and user input data are obtained on this software. Real time display of temperatures and pressures are available in chart form. This facilitates different training activities such as the recording of the vapor-pressure curve of the cycle, the expander isentropic efficiency and power output, the determination the heat input and the overall energy conversion efficiency.

Students will be trained to operate the ORC system according to the following procedure:

1. Run the oil gear pump which circulates oil between heater tank and evaporator.
2. Switch on heater 1 and heater 2.
3. Switch on chiller.
4. As soon as oil temperature reaches 80°C, switch on the R134a pump.
5. Generator load relays R1 and R2 are to be off state.
6. When the evaporator pressure reached to 15 bar, open the solenoid valve at expander inlet.

7. Monitoring the superheating degree and subcooling degree including the pressure at evaporator inlet and outlet points.
8. Monitoring the shaft speed of the expander.
9. Generator electrical load can be adjusted as follows: (i) both R1 and R2 are off (ii) R1 on and R2 off, and (iii) both R1 and R2 are on.
10. Heat input can be adjusted as follows: (i) Heater 1 on (ii) Heaters 1 and 2 on (iii) Heaters 1, 2 and 3 on (Heater 4 is reserved).
11. Stopping procedure: (i) stop the R134a pump (ii) switch the heaters off; (iii) stop the gear pump for oil circulation; (iv) switch the chiller off.

In case of failures, the safety procedures switch off the R134a pump to stop R134a flowing into the evaporator and open the solenoid valve to release pressure in the evaporator.

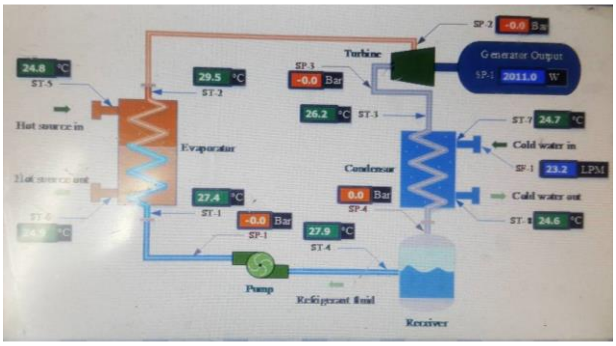

Figure 5: PLC data acquisition and control with LCD touch screen (in off-mode operation)

4 CONCLUSIONS

Within the context of 'Skybelt' project, co-funded by the EU under the framework of the Erasmus+ programme and coordinated by eCampus University, Italy, three Asian universities equipped their laboratories with ORC test bench to train their students at different levels in the field of ORC systems. These universities are University Putra Malaysia, University Sains Malaysia, and Naresuan University. All the ORC test benches are based on subcritical and non-regenerative ORC units using converted scroll compressor as the expander. Electrical heaters are used to supply heat using a diathermic oil circuit and chilled water is used as cooling medium. The ORC systems have been designed to exploit low-temperature heat sources as renewables sources like solar thermal to promote their integration in building for combined heating and power production.
Students are going to use the test benches in different modules at Partner Countries Universities with the aim of fostering knowledge and providing expertise in the control and operation of such systems at small-scale.

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