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ScienceDirect

Energy Procedia 123 (2017) 281–288

Energy Procedia

www.elsevier.com/locate/procedia

1st International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF 2017, 19-20 April 2017, Berkshire, UK

Techno-economic survey and design of a pilot test rig for a trilateral flash cycle system in a steel production plant

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Abstract

In recent years the interest in recovering rejected low-grade heat within industry has intensified. Around 30% of global primary energy consumption is attributed to the industrial sector and a significant portion of this is rejected as heat. The majority of this wasted energy is available at temperatures below 100°C and as such conventional waste heat to power conversion systems cannot economically recover the energy, producing simple pay backs that are unacceptable to industry. The Trilateral Flash Cycle (TFC) is however a promising technology with the ability to harness the rejected heat found in these low grade waste streams. The current research work presents a techno-economic assessment of the installation potential for a low grade heat to power conversion system using a TFC system. In particular, thermodynamic modelling is utilised to estimate the expected energy recovery and, in turn, the potential savings achievable through the TFC solution. The survey investigated three diverse and challenging heat sources at steel production plants. Annual energy recovery from the chosen heat source is expected to be 782 MWh. Prior to the upscaling of the system to the 2MW waste thermal power, a pilot test rig was designed and built. Preliminary tests showed a net electrical power output up to 6.2 kW and an overall efficiency of 4.3%.

Peer-review under responsibility of the scientific committee of the 1st International Conference on Sustainable Energy and Resource Use in Food Chains.

Keywords: trilateral flash cycle; waste heat recovery; steel production; industrial energy recovery

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Peer-review under responsibility of the scientific committee of the 1st International Conference on Sustainable Energy and Resource Use in Food Chains.
10.1016/j.egypro.2017.07.242

Nomenclature

c_p	Specific heat at constant pressure [J/(kg K)]
h	Specific enthalpy [J/kg]
$\dot{m}$	Mass flow rate [kg/s]
T	Temperature [°C]
η	Efficiency [-]

1. Introduction

Recovery of heat for conversion to power is of growing importance in today's industrial sector; energy demands and prices are continuing to rise in the global market, and there is increasing scrutiny of industrial environmental impact. Studies find the potential of theoretical global waste heat to be 68.2 TWh, and that 63% of this potential occurs at temperatures below 100°C [1]. As such, low temperature waste streams are once again being examined as potential power sources [2]. These can be found in numerous manufacturing industries in the form of thermal streams and despite containing a significant amount of energy, this energy is often rejected to atmosphere or requires additional energy input to cool. Waste heat from industrial processes, hot flue gasses from gas turbine generators, and heat rejected from nuclear reactors are just some of the sources available [3]. Recovering this energy will help to reduce thermal pollution and generating electricity will play a key role in decreasing overall plant operating costs [4]. Utilising waste heat for production of electricity is therefore increasingly important.

The total heat recovery opportunity for the industrial sector is estimated to lie in the region of 36-71PJ (10-20TWh) [5]. The Iron and steel sector counts for almost half of this potential, which is unsurprising since it is the largest industrial heat user, with an annual energy demand of 213PJ. There are several key processes involved in the making of steel, but by far the largest energy consumer of any integrated plant is the blast furnace. This facility has low exhaust temperatures around 150°C, which puts the recovery of this energy firmly into low-temperature waste heat potential. In fact the iron and steel industry has the highest potential for recovery of low grade heat (below 250°C) of all industrial sectors [5].

The growing interest in technologies for conversion of heat to power is not only limited to the steel industry. In fact, applied research on the topic of waste heat recovery is extensive and has been completed for several different sectors including: ceramics [6], paper and pulp [7], metallurgical [8], oceanic [9], and solar thermal [10]. In particular, there is a wealth of literature around conventional heat recovery cycles used in existing power plants, such as organic Rankine cycle and Kalina cycle [4,11]. The Trilateral Flash Cycle (TFC) is however still largely unexploited. Literature for the TFC is noted by Ian Smith et al. at City University London, where a cycle conceived especially to optimize power recovery from heat resources less than 250°C, is presented [12,14]. Included is detailed technical analysis which shows that the gross power output from the TFC exceeds that of any simple organic Rankine cycle over the entire low-temperature range [13].

The present paper describes the methodology required to develop a TFC system for low grade heat to power conversion applications, with reference to the working fluids at the state of the art. Waste heat recovery opportunities in Iron and Steel have made Tata steel an ideal demonstration partner for this TFC system. As such, three opportunities for demonstration sites at Tata Steel locations are reviewed from technical and economic perspectives, and the complexities considered when designing the pilot-test rig are discussed. Preliminary experimental results are eventually presented.

2. TFC fundamentals and Thermodynamic modelling

In a TFC system, heat gain is achieved without phase change of the organic working fluid, and the expansion process therefore starts from the saturated liquid state rather than a vapour phase. With reference to the plant layout and T-s diagram displayed in Figures 1 and 2, the working fluid is pressurized adiabatically, heated at constant pressure to its saturation point, expanded adiabatically as a two-phase mixture and eventually condensed at constant pressure.

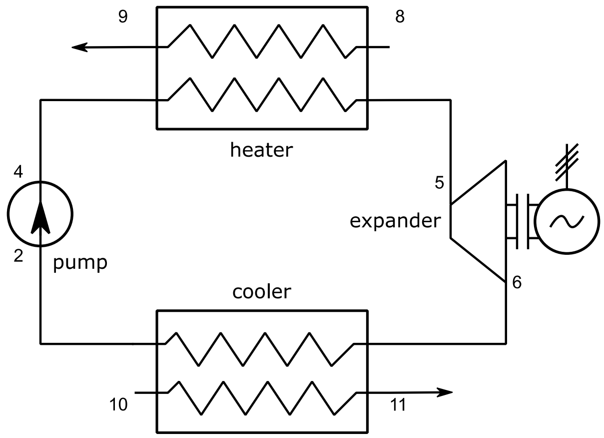

Fig. 1. TFC system components.

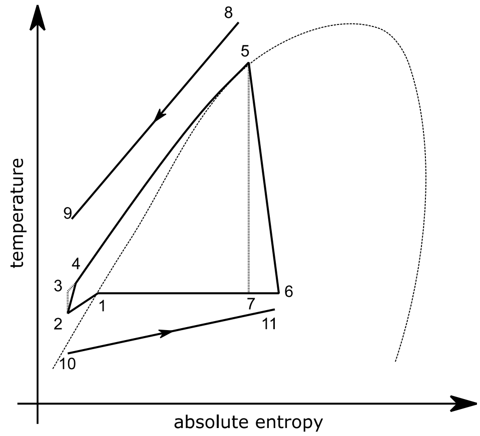

Fig. 2. TFC system temperature-entropy chart.

In order to provide insight on the actual recovery potential achievable with a TFC system, with reference to the working fluids at the state of the art, a theoretical model has been developed. The model is based on steady state energy balances at the heater and cooler as well as on the isentropic efficiency definitions for a pump and expander. Equations are reported in Table 1 and have been implemented in the Engineering Equation Solver software platform, which additionally provides thermophysical properties of organic working fluids and standardized mixtures.

Table 1. Governing equations to develop an essential TFC modelling platform

Heater	$\dot{m}_{hot} c_{p,hot} (T_8 - T_9) = \dot{m}_{wf} (h_B - h_A)$	(1)
Cooler	$\dot{m}_{cold} c_{p,cold} (T_{11} - T_{10}) = \dot{m}_{wf} (h_D - h_C)$	(2)
Pump	$\eta_{pmp} = (h_3 - h_2)/(h_4 - h_2)$	(3)
Expander	$\eta_{\exp} = (h_5 - h_6)/(h_5 - h_7)$	(4)
Cycle efficiency	$\eta_{cy} = \dfrac{\dot{m}_{wf} \left((h_5 - h_6) - (h_4 - h_2) \right)}{\dot{m}_{hot} c_{p,hot} (T_8 - T_9)}$	(5)
Overall efficiency	$\eta_{tot} = \eta_{cy}\, \eta_{mech}\, \eta_{el}$	(6)

As the working fluid is not evaporated in the heater, the mass flow rate is comparatively high to other cycles, and the work of the refrigerant feed pump is therefore considerable. With this in mind, an assessment of the working fluid and the relative performance advantages has been carried out using a screening procedure. In particular, with reference to a sample waste heat stream of 1 kg/s at 90°C and the design parameters reported in Table 2, Figure 3 reports a comparison of different working fluid performances in terms of net electrical power output, and relevance of pumping power expressed as a ratio between the enthalpy drop at the expander and the enthalpy rise at the pump. Due to its low vapour pressure, R245fa demands relatively low pumping power, and as such the parasitic losses associated with pumping liquid refrigerant are reduced, reducing the payback time of the system. R245fa is therefore the chosen working fluid for the pilot test rig.

Table 2 – Input data for the simulations reported in Figure 3

Pump isentropic efficiency	40%	Inlet water temperature (T_{10}) at condenser	15°C
Expander isentropic efficiency	75%	Condensation temperature	20°C
Mechanical efficiency	98%	Sub cooling	NO
Electrical efficiency	95%	Hot source	Flue gas

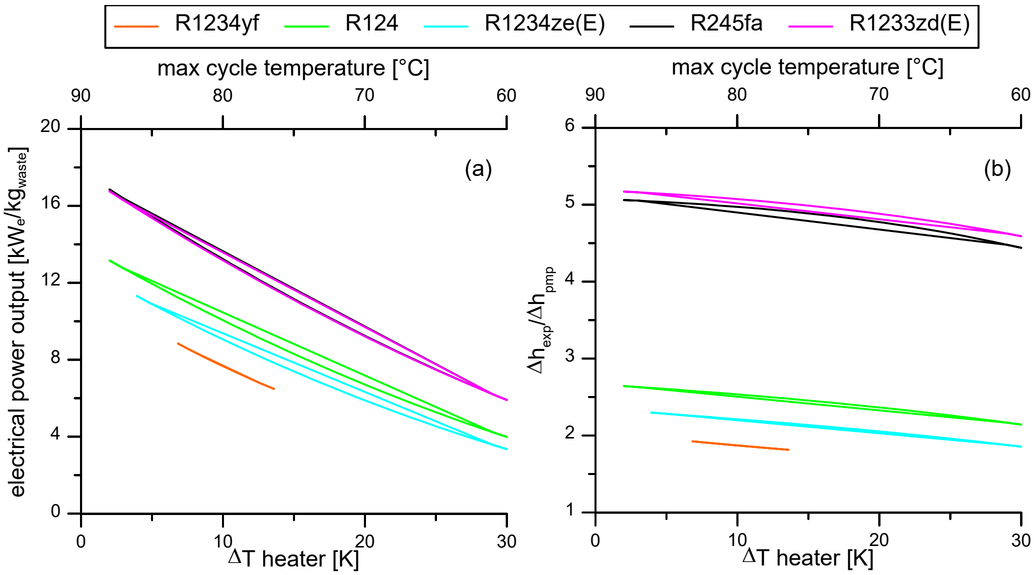

Fig. 3. Theoretical analysis of working fluid performance in a TFC system

3. Tata Steel UK Application

It is recognized that there remains significant loss of thermal energy at steel making sites. Therefore the thermal size and temperature of unrecovered energy streams were reviewed at two Tata Steel sites in the UK. The motivation behind this review was to identify a viable location for the TFC demonstration site, which would provide an uncomplicated installation typical of other unrecovered energy streams, and sufficient transferable data regarding the TFC system. Three prospective energy streams, generated by the steel manufacturing process and energy generation on the sites were identified, as described in Table 3. Potential electrical power generation and ease of installation for each stream have been investigated.

Table 3. Design data for TFC system in three Tata Steel applications

Application	Flowrate (m^3/h)	Inlet Temperature (ºC)	Outlet Temperature (ºC)	Thermal Power of Waste Stream (kW)	Number of Hours Running	MWh per year generated
Tata Steel Heat Source A	33,820 (gas)	250	95	1478	7000	833
Tata Steel Heat Source B	63,000 (gas)	200	85	2415	7000	1001
Tata Steel Heat Source C	37.4 (liquid)	70	24	2000	8600	782

3.1. Tata Steel Gas Heat Sources A & B

Two promising gas heat sources were identified at one Tata Steel location, both attributed to the steel painting process. Unrecovered heat from exhaust gases are considered typical within steel making, and are often challenging to recover due to a number of considerations, these heat sources were therefore studied in more detail. Exhausted gas temperature was at 250°C with a flow rate of 33,820 m^3/h, for Heat Source A. For Heat Source B, exhausted gas was at 200°C with a flow rate of 63,000 m^3/h. According to equations by Verhoff & Banchero, the acid point of sulphuric acid in the exhaust gas was calculated to be 69.4°C, with a conversion rate of SO_2 to SO_3 as 100% [15]. Hence, it would be crucial to ensure that exhaust gasses remain above 69.4°C within heat exchangers to avoid corrosion from acidic condensate. With this in mind, exhaust gas temperatures of 95°C and 85°C were considered at the TFC heater outlet for Heat Source A and Heat Source B applications respectively.

To install the TFC heater at the either locations, modifications would be required. Either the 1m x 1.8m ducts running to the stack would need to be modified to each hold a heat exchanger, or the 30m stack would need lifting to install a single heat exchanger; such modifications would be required at either location if chosen. Installation would therefore have a substantial financial impact on the payback of the system. In fact despite the 833-1001MWh potential electricity generation, the modifications to site produce an initial simple pay back that is not considered acceptable with respect to the industrial target.

3.2. Tata Steel Liquid Heat Source C

An alternative application was investigated in detail at a second Tata Steel production site. Running through the site is a 26km steam main pipe network, with 11bar_g and 44bar_g steam that is predominantly raised using gases produced in the steelmaking process. The generation and use of this steam on-site in various processes and locations, produces many heat recovery opportunities. At one opportunity, Heat Source C, water at temperature of 60°C is cooled via two heat exchangers using river water, before it is sent to the water treatment plant. A survey of Heat Source C showed that the temperature could be increased to 70°C through insulation and diverting of other lower temperature sources. At 60°C a flowrate of 15.4kg/s will generate 100kW of electrical power. At 70°C a flowrate of 10.39kg/s will generate 100kW, and therefore 783MWh of electrical power per year, as seen in Table 3.

The modifications anticipated for this installation are minimal. Local process cooling water can be exploited for the TFC condenser, but requires careful selection of heat exchanger to match the water quality. This could have an associated financial impact. Nevertheless, the simple pay back model of this Tata Steel demonstration site is within the acceptable limits. In fact, despite generating 51-219MWh less than applications A and B, Heat Source C's minimal installation costs support a more commercially attractive demonstration site. A further benefit of this location is the opportunity to demonstrate the capabilities of the TFC at lower operating temperatures, where currently technology for low-temperature waste heat recovery is not commercially viable. The Tata Steel Heat Source C location has therefore been chosen as the demonstration site. Design specifics are reported in Table 4.

Table 4: Tata Steel Final TFC Design Specifics

Stream	Flowrate (kg/s)	Inlet Pressure (bara)	Outlet Pressure (bara)	Inlet Temperature (ºC)	Outlet Temperature (ºC)
Waste heat stream	10.39	4	3.5	70	24
Refrigerant stream	31.4	5.47	1.18	66	19
Condensing water stream	90.85	4	3.5	12	17

4. Design of Pilot Test Rig

As shown in Table 3, thermal power of the low temperature waste heats stream for the Tata steel application will be 2 MW. Therefore, in order to gain know-how on the TFC technology, a test facility with the ability to emulate the variety of waste heat streams found in industry was designed and built at a Spirax Sarco UK. A scheme of the pilot TFC system is reported in Figure 4.

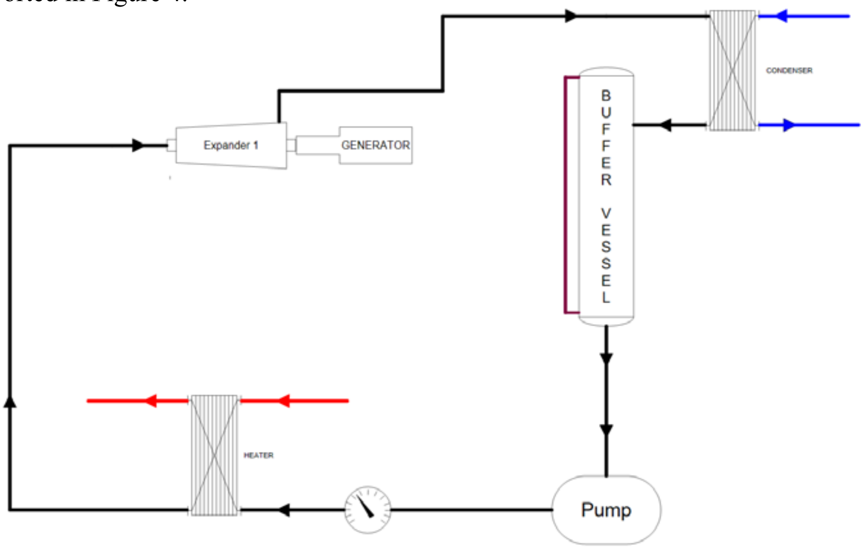

Fig. 4. Final TFC System Design.

The heat source is generated by an EasiHeat™ packaged heat exchanger. This system utilizes a gasket heat exchanger to transfer heat from 10bar$_g$ steam to an atmospheric water stream. A set point between ambient temperature and 98°C (allowing for 2K of sub-cooling) is programmed into the controller, and a control valve maintains the stream steady at this temperature. A water pump capable of flow rates up to 80m^3/h and a flow meter are also installed in the line. Together these components provide the capacity to emulate low-temperature thermal waste streams up to 250kW, thus supporting the completion of a detailed experimental campaign.

The plate heat exchanger chosen as the heater for the TFC pilot test rig includes a 2K approach and 0.116 bar pressure drop to maximize the heat transfer. However, this is not the most commercially applicable solution, as achieving these efficiencies is costly. Therefore, in the future upscaling of the rig, a thermo-economic study will be carried out taking into account cost, pressure drop, temperature approach, service life and associated TFC electrical power generation.

The presence of liquid during the expansion process discards several types of expanders (e.g. turboexpanders) and as such twin-screw expanders have been identified as the most suitable technology for this application. Connection of the expander and synchronous generator is made through a speed reduction pulley system. This reduces the expander speed from 3500RPM down to 1500 RPM which is the nominal generation speed for the generator, whose electrical nominal power is 15 kW. The scaling factor of the TFC pilot test rig in comparison to the final application is 10; hence, thermal power input at design conditions are 0.2 MW rather than 2 MW and the expected net electrical power output is 10 kW.

Downstream of the expander, the two phase liquid is then passed into the condenser, before passing into a buffer vessel to maintain head for the pump. The condensing heat exchanger chosen has a 4K approach and a maximum 0.5bar pressure drop. Due to the high heat recovery in the TFC heater, in an industrial application it will be possible to reuse any existing cooling system, previously used to cool the waste heat stream, to remove the heat from the TFC condenser. Due to this, and the TFC's ability to complete the entire cooling job, no additional cooling stream is required, as in conventional ORC systems. The cost of the heat sink system is therefore reduced considerably.

The heat rejection system in the pilot test-rig is a cooling tower. As concerns the instrumentation, pressure and temperature sensors are installed across each component of the system. Working fluid mass flow rate is measured through a flow meter installed downstream of the pump, as done for both the hot and cold water sources.

A photograph of Spirax Sarco's Trilateral Flash Cycle Rig is shown in Figure 5. Ease of testing and optimisation, as well as health and safety have been taken into consideration in the build of the rig. TFC system performance is controlled through the flowrate of the refrigerant via a PLC, and an electrical panel with controllers govern the hot water and cooling streams.

A best practice start up and shut down procedure for the test-rig has been developed. This involves first generating the waste hot water stream using the EasiHeat™ packaged heat exchanger, and then applying a load to the generator via the connected load bank. The cooling water circuit can then be started, before finally beginning flow of the refrigerant for the TFC part of the system. In this order the heat source and sink are secured before any mechanical or electrical power is generated; this has been found to minimize technical performance issues.

Health and Safety of the test-rig has also been of the upmost importance, and continuous improvement has been exercised throughout development. To avoid over speeding of the expander, a tachometer has been installed, and connected to an individual safety relay to commence immediate shut down when 5000RPM, 85% of the expanders limit, is reached. This works in the same way as the installed emergency stop button; all electrical power to the rig is removed, and a normally closed valve cuts off the flow of refrigerant to stop the expander turning.

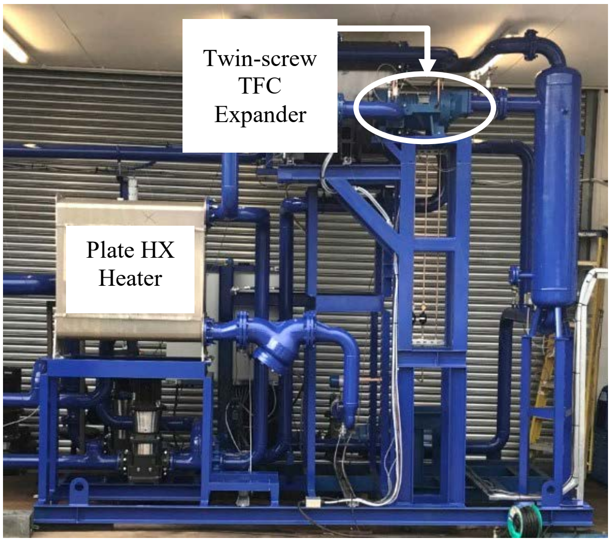

Fig. 5. TFC Pilot Test-rig at Spirax Sarco.

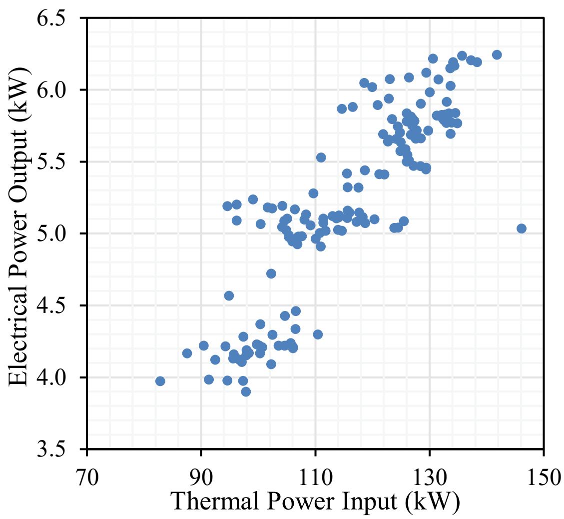

Fig. 6. TFC Pilot Rig initial testing results.

5. Initial Testing

The TFC pilot rig has been run successfully with promising results. A section of results from the initial test program are included in Figure 6. The variety of thermal power inputs reflect inlet waste stream temperatures varying from 70˚C to 80˚C, with outlet temperatures consistently below 25˚C. Results show that an increase in thermal power, produces an increase in electrical power. Maximum power output for the testing session was 6.2kW, based upon a thermal power input of 141.8kW. Most importantly, the results demonstrate the ability to complete the total cooling job, which is a significant benefit of the TFC system. In doing so, the total potential of the waste heat stream is utilized, and no additional cooling is required, as in an ORC system. Overall the results show a correlation between thermal power input and electrical power output, and efficiency's reflect the thermodynamic modelling completed during the design.

It is however notable that currently control of the cycle via the PLC is difficult, acting as a barrier to optimisation of the rig. An improved automated control system has been proposed which involves an iterative method utilising pumps, rotational speed of the expander, temperature, and pressure feedback to determine the optimal operating conditions. This system is now in development, and an extensive testing program is planned to support this.

6. Conclusions

In the paper, the development of a TFC pilot test rig for low grade waste heat to power conversion has been presented. Discussion around the potential demonstration sites has been included with reference to a steel production plant, and in particular, the impact that installation has on commercial business case. This review includes process data and associated potential electrical power generation for a TFC system. In addition to thermodynamic analysis, the key role of economic viability for the development of heat recovery technologies is discussed.

Once the most suitable industrial site was chosen, the thermodynamic modeling platform supported selection of the design specifics for the full scale TFC system. With reference to these operating conditions, a pilot test rig with a scaling factor of one tenth was designed and built at Spirax Sarco UK. Expected power output for a 200kW thermal input should be 10 electrical kW. Preliminary tests demonstrated the ability to reach 6.2 kW with a thermal power input of 141.8 kW (4.3% efficiency).

A limitation of the pilot rig presented is the control of the components and this is reflected in the results demonstrated. Due to the simplified nature of the control system, optimisation of the rig based upon several different inputs is difficult, and future studies on the rig will aim to develop this system further.

Acknowledgements

Authors would like to acknowledge financial support for the research presented in this paper from: i) the European Union's Horizon 2020 research and innovation program under grant agreement No. 680599, ii) Innovate UK under project no. 61995-431253, iii) Engineering and Physical Sciences Research Council UK (EPSRC), Grant No. EP/P510294/1.

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