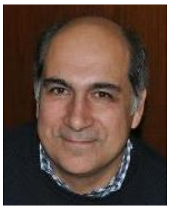
EXPERIMENTAL STUDY OF SINGLE PHASE PRESSURE DROP IN A VEHICLE HEAT-REGENERATOR

ESTUDO EXPERIMENTAL DA PERDA DE CARGA EM ESCOAMENTO MONOFÁSICO NUM PERMUTADOR DE CALOR PARA RECUPERAÇÃO DE ENERGIA TÉRMICA EM VEÍCULOS

O. R. Gouveia, A. Almeida, H. Santos, J. Morgado, N. Martinho, J. F. Pereira

ADAI-LAETA, IPLeiria delegation, School of Technology and Management, Polytechnic Institute of Leiria

ABSTRACT

Waste heat recovery (WHR) by means of Rankine cycle (RC) is a promising technology to further reduce fuel consumption in internal combustion engine (ICE) equipped vehicles. The design and performance optimization of the Rankine cycle system components are then key factors to optimize the overall vehicle efficiency. One of the main components of a RC based system is the heat exchanger (HEX), which is responsible for the thermal energy transfer between the ICE waste heat source and the RC working fluid. Considering ethanol as the practical application RC working fluid, almost 70% of the HEX volume corresponds to the pre-heater section. With this in mind, this paper presents an experimental study on the single-phase working fluid pressure drop through the tubes and return chambers of a HEX for a Rankine cycle waste heat recovery (RC-WHR) system. Based on a detailed geometrical characterization of the HEX on the working fluid side, a predictive analytical model for the pressure drop through the HEX was developed. We determine the pressure drop in HEX tubes and return chambers for a wide range of practical operating conditions.

RESUMO

A recuperação de energia térmica através do ciclo de Rankine (CR) é uma tecnologia promissora no sentido de reduzir o consumo de combustível em veículos equipados com motor de combustão interna (MCI). Nesse sentido, a otimização dos componentes do CR torna-se crítica para a otimização da eficiência do veículo. Um dos principais componentes constituintes do sistema CR é o permutador de calor (HEX) que é responsável pela transferência de energia térmica entre a fonte de calor do MCI e o fluido de trabalho do CR. Considerando etanol como o fluido de trabalho, sensivelmente 70% do volume do HEX corresponde à secção de pré-aquecimento. Nesse sentido, este artigo apresenta um estudo experimental da perda de carga do fluido de trabalho em escoamento monofásico nos tubos e camaras de inversão de um HEX para aplicação num sistema de recuperação de energia através de ciclo de Rankine. Com base na caracterização detalhada da geometria do HEX para o lado do fluido de trabalho, foi desenvolvido um modelo para a perda de carga. Foi determinada a perda de carga nos tubos e nas camaras de inversão para uma gama alargada de condições práticas de operação.

1. INTRODUCTION

The modern automotive Internal Combustion Engine (ICE) rejects up to 50% of the total fuel chemical energy in the form of waste heat, Domingues et al. (2013). Worldwide regulations impose further ICE emissions and fuel consumption reductions. So that, there is a growing interest in technologies that allows for the recovering the exhaust gas thermal energy to further improve the overall ICE efficiency. This has been an intensified area of research in the last decade, where numerous methods including turbocompounding, thermoelectric generators and fluid bottoming cycles (e.g., Rankine cycle) have been proposed and demonstrated for on-road vehicles, Wang et al. (2011).

The potential fuel consumption reduction using any heat-to-power conversion technology depends on the ICE application. Highest benefits are expected for long-haul truck applications, which involve extended time of running at near steady speeds. As a result, it has been shown that such technologies can play a significant part in achieving future efficiency goals for Heavy Duty Diesel Engines (HDDE). For heavy-duty trucks, recent studies published by AVL; Behr; Bosch; Voith; Ricardo and Volvo; and Cummins have shown that the RC based systems can reduce the fuel consumption by 3% to 6%, Latz (2016).

One of the main components of a RC based system is the heat exchanger (HEX), which is responsible for the thermal power transfer between the waste heat source and the working fluid (WF). The HEX must be designed to provide the best trade-off between efficiently transferring the energy and having suitable dimensions for integration into the target vehicle. In addition, the pressure drop on the working fluid side must be as low as possible in order to increase the pump efficiency and consequently to reduce its volume and weight.

Considering that almost 70% of the HEX volume corresponds to the pre-heater section of the HEX, Santos et al. (2016), the present work presents an experimental assessment on the pressure drop in single-phase flow inside the pipes of a HEX for an automotive RC-based WHR system.

2. LITERATURE REVIEW

2.1. Continuous pressure drop

When fluid flows through a pipe, energy is dissipated. This energy is expended in overcoming viscous friction, Pienaar (2004). The continuous pressure drop can be evaluated as follows:

$$\Delta P = f \frac{L}{D} \frac{1}{2} \rho v^2 \tag{1}$$

where f is a dimensionless friction factor, L is the pipe length, D is the pipe hydraulic diameter, ρ is the working fluid density, and v is the average fluid velocity in the pipe.

2.1.1. Friction factor theory

For the friction factor f, both the Darcy friction factor, f_D and the Fanning friction factor, f are used. By definition, $f_D = 4f$. In laminar flow regimes, the Poisseuille number, defined as $Po = f_D \cdot Re$, is constant. The Poisseuille number depends on the geometry of the channel cross section, being 64 for circular channels, Steinke and Kandlikar (2006). So that for a laminar flow regime in a circular cross section channel the Darcy friction factor f_D became:

$$f_D = \frac{64}{Re} \tag{2}$$

For a turbulent flow regime, mainly because of the thin boundary layer, the Darcy friction factor f_D depends on both Reynolds number and pipe roughness, Kiijarvi (2011). The Darcy friction factor in turbulent flow can be obtained by using the Moody diagram or by solving the implicit Colebrook-White equation:

$$\frac{1}{\sqrt{f_D}} = -2 \log_{10} \left(\frac{\varepsilon/_D}{3.7} + \frac{2.51}{Re\sqrt{f_D}} \right) \tag{3}$$

where $\varepsilon/_D$ is the relative roughness of the pipe. Because of its implicit nature, the determination of the friction factor using the Colebrook-White equation requires an iterative procedure. In order to avoid this, several explicit correlations have been introduced. Among them, the Blasius equation is the simplest one:

$$f_D = 0.316 Re^{-0.25} \tag{4}$$

The Blasius equation does not account for the pipe roughness, and so that for a rough pipe it can only be used as an initial value. Haaland (1983) derived an explicit equation for Darcy friction factor that accounts for the pipe roughness:

$$\frac{1}{\sqrt{f_D}} = -1.8\log_{10}\left(\frac{\varepsilon/_D}{3.7}^{1.11} + \frac{6.9}{Re}\right) \quad (5)$$

The accuracy of the results obtained with the Haaland equation is within ±2% for Re>3000, Kiijarvi (2011). In the present work, the Haaland equation was used for the determination of the Darcy friction factor f_D under transitional and turbulent flow conditions.

2.1.2. Hydrodynamically developing flow

The hydrodynamically developing flow (HDF) becomes quite important for channels with low aspect ratio (*x/D*). For compact systems, as the heat exchanger (HEX) under investigation, the HDF can dominate the entire flow length in the pipes of the HEX. To characterize the HDF, the non-dimensional axial distance was defined:

$$x^+ = \frac{x}{D \cdot Re} \quad (6)$$

where x^+ is the non-dimensional flow distance and x is the axial flow direction location. It is commonly accepted that for a value of x^+>0.05, a fully developed flow regime is attained Steinke and Kandlikar (2006). According to Olivier (2009), the use of the Poisseuille relation for laminar regime (see Eq.2) in HDF would be inappropriate, as it underestimates the experimental friction factor. In order to account for the friction factor increase under HDF, in the present work an apparent friction factor f_{app}, instead of the f_D was used. Shah and London (1978) developed the following correlation for the apparent Fanning friction factor:

$$f_{app}Re = \frac{3.44}{Re} + \frac{fRe + \frac{K_\infty}{4x^+} + \frac{3.44}{\sqrt{x^+}}}{1 + \frac{0.000212}{x^{+2}}} \quad (7)$$

where K_∞ is the excess of pressure drop number in the HDF, given by Shah and London (1978) as $K_\infty = 1.2 + \frac{38}{Re}$ and $f{\cdot}Re$ is the constant value given by the Poisseuille relation.

2.2 Singular pressure drop

In addition to the continuous pressure drop that occurs in the HEX core pipes, the overall pressure drop value through the HEX also includes singular pressure losses due to geometrical changes that introduce disturbances in the working fluid flow. In fact, as an example, the working fluid experiences entrance losses as it enters the HEX core due to a sudden flow area reduction and, oppositely, losses due to a sudden flow area expansion at the core exit. These local or singular pressure drop represent additional energy dissipation in the fluid flow, which are due to secondary flow patterns induced by curvature or recirculation and can be expressed, Astakhov and Joksch (2012):

$$\Delta P = k\frac{1}{2}\rho v^2 \quad (8)$$

where ΔP is the singular pressure drop value, ρ the fluid density, v the highest average velocity experienced in the cross sections involved in the geometrical change and k is the local loss coefficient inherent to the geometrical singularity.

3. EXPERIMENTAL SETUP

3.1 System layout

An experimental setup was designed and constructed to test the HEX in a RC-WHR system. The RC-WHR system layout is depicted in Fig. 1.

As schematically shown in Fig. 1, the established RC system has a main working fluid loop (represented as a blue line) and two parallel security circuits (represented as gold and dark blue lines). The main working fluid loop consists of the heat exchanger (HEX), which corresponds to the test section, a diaphragm pump, a mass flow meter, an expander valve, an air cooled condenser and a reservoir. The working fluid is pumped from the reservoir to the HEX's inlet. Between the pump and the HEX, a mass flow meter was installed.

3.2 Test section: Heat exchanger (HEX)

The HEX test section consists on a crossflow tube heat exchanger, as schema-

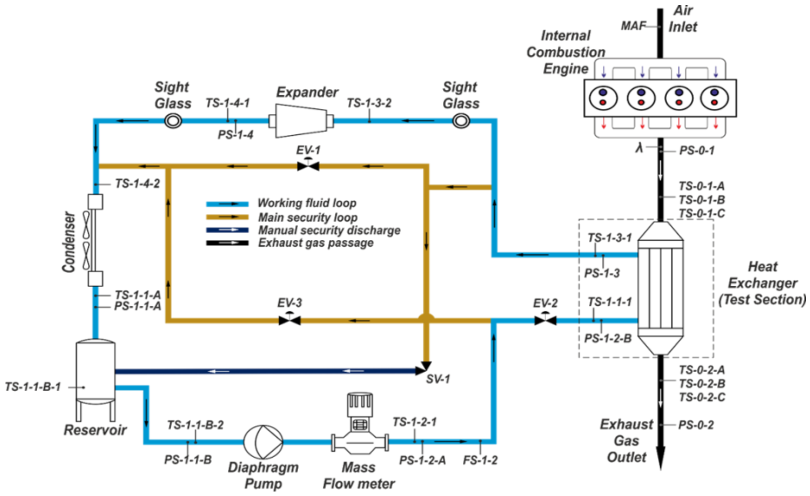


Fig. 1- RC-WHR system layout

tically shown in Fig. 2 and 3. The exhaust gas flows across the HEX and the working fluid flows inside the tubes. Furthermore, the working fluid presents a multipass flow arrangement through the pipes of the HEX core with return chambers at the top and at the bottom. The main characteristics of the studied HEX are presented in Table 1. Fig. 3 represents the sectioned heat exchanger according to the different geometry changes encountered in the WF circuit.

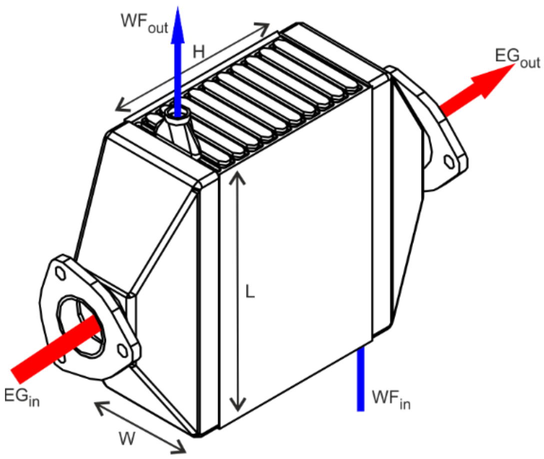


Fig. 2 – Schematic representation of the main dimensions of the HEX and flow arrangement

Table 1 – Main characteristics of the HEX.

Flow arrangement	Cross flow
Length (L)	214 mm
Width (W)	88 mm
Height (H)	146 mm
Total Volume	2.7 L
Nº of tubes per row	10
Nº of rows	21
Tube bank arrangement	Staggered
Tube inner diameter	4.5 mm

3.3 Instrumentation and data acquisition

The experimental facility uses 16 K-type thermocouples, 8 pressure transducers, 1 working fluid flow meter, 1 mass air flow meter (MAF) and 1 Lambda sensor. As depicted in Fig. 1 the working fluid temperature measurements upstream and downstream to the HEX was carried out by the thermocouples TS-1-1-1 and TS-1-3-1 respectively, with an accuracy of ± 0.75 %. The static pressure measurements upstream and downstream of the HEX by PS-1-2-B and PS-1-3 were performed by pressure sensors with an operating range of 0 to 9 bar with an accuracy of ± 0.5 %. In addition, a differential water manometer was used to determine the WF pressure drop. The WF mass flow rate was measured by means of ISOMAG 501 electromagnetic flowmeter, which allows a maximum operating pressure of 16 bar and an accuracy of ± 0.2 %. Two data acquisition board from National Instruments were used: the PCI-6221 and the PCI-6225. Each data acquisition board is connected to a signal conditioning board. The modules used for the thermocouples incorporates a cold junction compensation. The data acquisition and system control are guaranteed by a dedicated software (Labview). The developed Labview software allows using data from the installed sensors to manage the required actuators for proper control of the system, display data in diagrams and graphics and save it for posterior analysis.

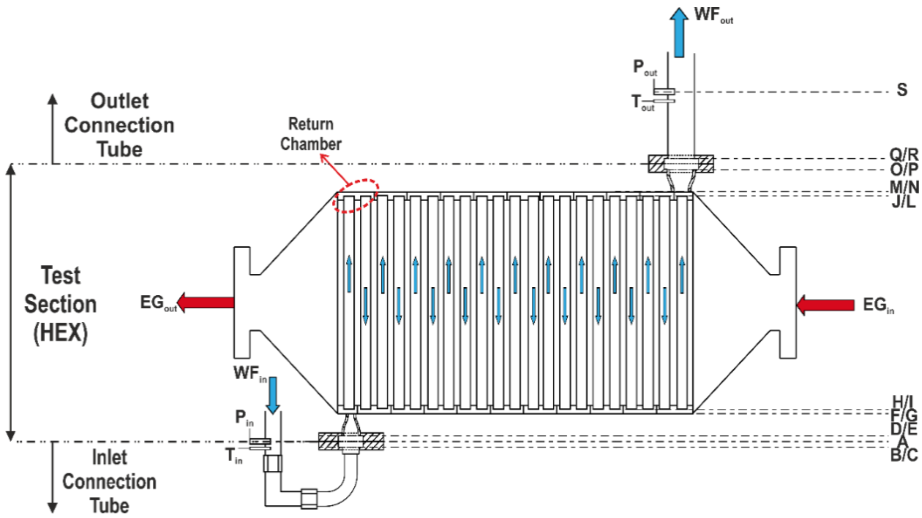


Fig. 3 – Detailed geometrical characterization of the HEX's Working fluid side.

3.4 Experimental procedure

For the determination of the working fluid pressure drop through the HEX, a wide range of mass flow rate was considered, from 1.9 to 41.7 g/s. The experiments were performed using water as working fluid and carried out at room ambient temperature (within 16.3ºC to 18.2ºC). Considering a mean water density ρ=998.76 kg/m^3 and a mean water dynamic viscosity μ=1059.6 Pa.s, the internal HEX core flow's Reynolds number at the different experimental data points range from 51 to 1072, which indicates that the HEX pre-heater section operates in a laminar flow regime. Table 2 presents a resume of the working fluid test conditions within the HEX core tubes.

Table 2 – Summary of the working fluid test conditions within the HEX core tubes.

Working fluid temperature [ºC]	16.3- 18.2
Working fluid mass flow rate [g/s]	1.9 - 41.7
Reynolds number at the HEX core tubes [-]	51 - 1072
*Average working fluid density [kg/m^3]	998.76
*Average working fluid viscosity [μPa.s]	1059.6

*properties calculated with REFPROP

The acquisition process of the above mentioned data was performed in steady-state conditions with the system presenting a stabilized value of working fluid mass flow rate. Then, the data were recorded for a period of approximately 10 seconds.

4. RESULTS AND DISCUSSION

This section presents a comparison of the experimental data against pressure drop predictions based on a developed model that allows the calculation of both the continuous and singular pressure losses through the HEX. The model requires a detailed characterization of the HEX tube side geometry (see table 1, Fig. 2 and Fig. 3). The developed model uses as input conditions the inlet static pressure and mass flow rate. Afterwards, the inlet dynamic pressure was calculated, as well as the total inlet pressure. Then, the pressure drop for the first section was evaluated. This process was repeated until the total pressure of the last HEX section is obtained. The temperature of the HEX was considered equal to the mean temperature of the inlet and outlet temperatures and constant throughout the HEX sections.

For the singular loss coefficient in the return chambers k_{RC}, there are no comparable published correlations. Furthermore, due to the difficulties in the geometrical characterization of the HEX return chambers, the singular loss coefficient of the return chambers was determined as a minimizer of the total mean relative error modulus obtained for a comparison of the experimental data against model predictions, Yin et al. (2002) also used this procedure. Fig. 4 depicts the variation of the mean relative error modulus as a function of the return chamber loss coefficient.

Fig. 4 reveals that the return chamber loss coefficient that minimizes the total mean relative error modulus is k_{RC}=2.4 , and so that this was the value considered in the model predictions. Yin et al. (2002) adopted a similar procedure. Shah and Sekulic (2003) proposed a theoretical model for pressure drop in headers (which has a similar geometry to the studied return chamber) in heat exchangers. Assuming an adiabatic header and a uniform flow distribution, the value of the proposed loss coefficient by Shah and Sekulic (2003) is 2.467, which is in good agreement with the present study result.

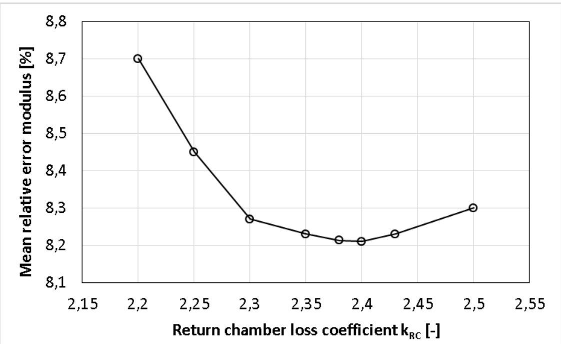


Fig. 4 – Variation of the mean relative error as a function of the return chamber loss coefficient.

Fig. 5 a) and b) show the experimental data and predicted pressure drop through the HEX and the relative error as a function of the working fluid mass flow rate, respectively.

As expected Fig. 5a) demonstrates that the pressure drop increases with the working mass flow rate, a comparison of the experimental and predicted data reveals a very good agreement. Fig. 5b) reveals that the relative error of the experimental data against the predicted pressure drop decreases as the working fluid mass flow rate increa-ses, for a working fluid mass flow rate higher than 12 g/s the relative error is within ± 5%.

For the optimization of the HEX it is important to know the relative contribution of the hydrodynamically developing flow (HDF) and return chamber loss coefficient on the total pressure drop through the HEX

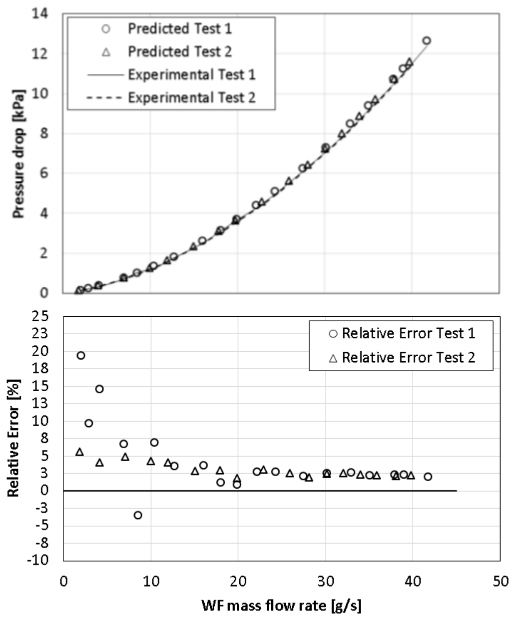


Fig. 5 – a) Experimental and predicted working fluid pressure drop through the HEX core as a function of the working fluid mass flow rate; and b) relative error as a function of the working fluid mass flow rate.

core. To this end, the pressure drop through the HEX was predicted for a HEX core with: i) developed flow without return chambers loss coefficient (reference case); ii) hydrodynamically developed flow (HDF) without return chambers loss coefficient (which accounts for the HDF effect); and iii) hydrodynamically developed flow (HDF) with return chambers loss coefficient (which corresponds to the practical operating conditions). Fig. 6 presents the predicted pressure drop of the working fluid through the HEX core for reference case (developed flow without return chambers loss coefficient), plus the HDF effect and plus the return chamber effect (practical operating conditions). The model predictions consider that the return chamber

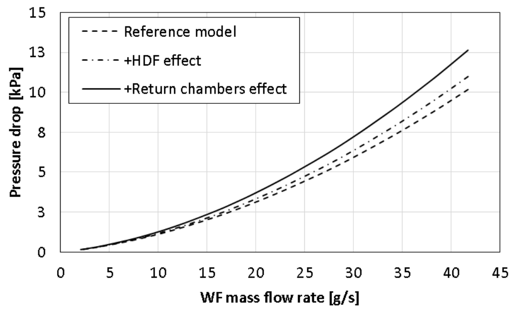


Fig. 6 – Predicted pressure drop of the working fluid through the HEX core for reference case (developed flow without return chambers loss coefficient), plus the HDF effect and plus the return chamber effect (practical operating conditions).

singular loss coefficient is constant, k_{RC}=2.4.

Fig. 6 reveals that the effect of the hydrodynamically developed flow (HDF) on the pressure drop is smaller than the effect of the singular pressure drop due to the return chamber.

Fig. 7 depicts the relative contribution of the continuous pressure drop (with HDF effect) and singular pressure drop due the return chambers as a function of the working fluid mass flow rate.

Fig. 7 reveals that for low working mass flow rates, the total pressure drop value in the HEX core is almost exclusively due to the continuous pressure drop losses that occur in the core tubes. Nevertheless, the contribution of the return chambers on the total HEX core pressure drop increases with the increase of the working fluid mass flow rate.

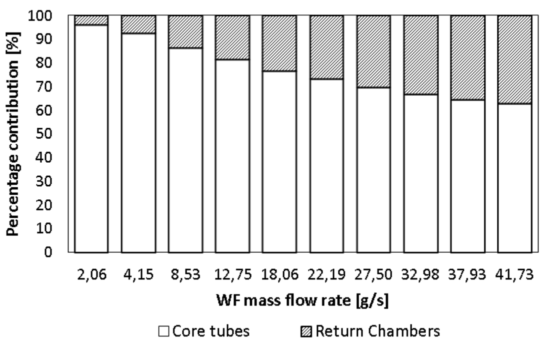


Fig. 7 – Relative contribution of the continuous pressure drop (with HDF effect) and singular pressure drop due the return chambers as a function of the working fluid mass flow rate.

5. CONCLUSIONS

The experiments and analyses demonstrated that friction factor correlation and singular pressure drop coefficients could be used to predict the continuous and singular losses in the HEX. When compared against the experimental data, the model predictions are within ± 5% for high working fluid mass flow rate, the discrepancies increase as the mass flow rate decreases. For low working fluid mass flow rates, the pressure drop in the HEX core is almost exclusively due to the continuous losses that occur in the core tubes. However, the contribution of the return chambers to the total HEX core pressure drop increases with the increase of the working fluid mass flow rate.

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REFERENCES

Astakhov, V.P. and Joksch, S.. Metalworking fluids (MWFs) for cutting and grinding fundamentals and recent advances 1st ed., Woodhead Publishing Series, 2012.

Domingues, A., Santos, H. e Costa, M. Analysis of vehicle exhaust waste heat recovery potential using a Rankine cycle, Energy, 49, p. 71-85, 2013.

Haaland, J.E. “Simple and explicit formulas for the friction factor in turbulent pipe flow. Journal of Fluids Engineering, pp: 89-90, 1983.

Kiijarvi, J.. Darcy friction factor formulae in turbulent pipe flow. Lunowa Fluid Mechanics Paper, pp.1–11, 2011.

Latz. Waste heat recovery from combustion engines based on the Rankine cycle. PhD Thesis Chalmers University of technology, 2016.

Olivier, J.A.. Single-Phase Heat Transfer and Pressure Drop of Water Cooled At a Constant Wall Temperature Inside Horizontal Circular Smooth and Enhanced Tubes With Different Inlet Configurations in the. PhD Thesis, University of Pretoria, 2009.

Pienaar, V.. Viscous flow through sudden contractions. PhD Thesis, Cape Town University, 2004.

Santos, H., Pires, N., Caseiro, D., Morgado, J., Pereira, J.P. and Martinho N. Experimental study of an evaporator heat exchanger for a

Rankine cycle vehicle waste heat recovery system, Journal of Clean Energy Technologies, 4 (5), p. 362-366, 2016.

Shah, R. and Sekulic, D.. Fundamentals of heat exchangers design, 2003.

Shah, R.K. and London, a. L.. Laminar flow forced convection in ducts, 16(170), pp.78–152, 1978.

Steinke, M.E. & Kandlikar, S.G.. Single-phase liquid friction factors in microchannels. International Journal of Thermal Sciences, 45(11), pp.1073–1083, 2006.

Wang, E.H. Zhang, H.G., Fan, B.Y. Ouyang, M.G. zhao, Y. and Mu, Q.H.. Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery. Energy, 36(5), pp.3406–3418, 2011.

Yin, J.M., Bullard, C.W., and Hrnjak, P.S. Single-phase pressure drop measurements in amicrochannel heat exchanger, Heat Transfer engineering, 23 (4), pp.3-12, 2002.