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par

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CONTRIBUTION TO THE STUDY OF WASTE HEAT RECOVERY SYSTEMS ON COMMERCIAL TRUCK DIESEL ENGINES

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La connaissance s'acquiert par l'expérience, tout le reste n'est que de l'information.
Information is not knowledge. The only source of knowledge is experience.
[Albert Einstein]

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Abstract

Fuel price increase as well as future fuel consumption regulations lead truck manufacturers to further enhance the current powertrain. In such a context, two waste heat recovery technologies appear as promising: the Rankine system as well as the thermoelectric generator. Both technologies are well studied within the past 30 years literature.
After a reminding of truck boundary conditions, this thesis work defines a 0-D modeling done under the engineering equation solver for both systems (approaches enabling to define the working fluid for the Rankine system). Then, for both systems a commercial tool is used to further investigate the two technologies.
For the thermoelectric generator this commercial tool, developed under Matlab, models a thermoelectric generator architecture (designed for mass production) developed in the frame of a research program. Parametric studies are done on the integration of a thermoelecric generator upstream the existing engine exhaust gas recirculation cooler. Main studies are done with Mg_2Si and $MnSi$ as thermoelectric materials but other materials are also considered.
A Rankine system design is presented and modeled under a well known commercial 1-D solver used within the automotive industry. Preliminary validations of the model based on supplier modeling data are presented as well as the modeling validation of the turbine component tested. Transient aspects are evaluated to better understand the behavior of the system and its bottlenecks. The amount of refrigerant in the circuit and the control schematic are also addressed. From these study, it appears that the thermoelectric generator technology is not yet mature for an integration into a long haul truck due too the low performance of thermoelectric materials. The Rankine system technology should handle a complete truck prototype testing to estimate its potential.

Keywords: Waste heat recovery, Rankine system, thermoelectric generator, truck, modeling.

Résumé

L'augmentation du prix du pétrole ainsi qu'une possible future réglementation des émissions de CO_2 encourage les fabriquants de véhicules industriels à trouver de nouvelles solutions pour améliorer encore la performance de la chaine cinématique. Dans ce cadre, deux solutions de récupérations d'énergie prometteuses sont très souvent rapportées dans la littérature: le système de récupération d'énergie par cycle de Rankine et le générateur thermoélectrique.
Après un rappel des conditions limites du fonctionnement d'un camion long routier, cette thèse démontre tout d'abort des modèles 0-D réalisés sous le solveur de calcul Engineering Equation Solver destinés à la meilleur compréhension de ces deux technologies (notamment le choix du fluide de travail pour le système Rankine). Puis, pour ces deux systèmes, des logiciels commerciaux sont utilisés.
Pour le générateur thermoélectrique, ce logiciel commercial développé sous Matlab dans le cadre d'un consortium de recherche, permet de modéliser une architecture inédite d'échangeur thermoélectrique (destinée à l'industrialisation). Des études paramétriques sont effectuées sur cette échangeur placé en amont de l'échangeur de recirculation des gaz d'échappement du moteur diesel. Ces études se basent principalement sur l'utilisation de deux matériaux prometteurs: le Mg_2Si et le $MnSi$ mais d'autres matériaux thermoélectriques sont aussi considérés.
Une conception du système Rankine est présentée et modélisée avec un solveur commercial 1-D très utilisé dans l'industrie automobile. Des validations partielles sont réalisées sur les composants se basant sur les données transmises par les fournisseurs mais également sur des résultats de test de composants (turbine). Ce modèle a ensuite permis d'étudier les transitoires du système pour mieux comprendre son fonctionnement. La charge en réfrigérant ainsi que le contrôle possible du système sont également abordés.
A partir de ces études, il semble que le générateur thermoélectrique ne soit pas encore mature pour son utilisation dans un camion long routier. En effet, les matériaux thermoélectriques devront encore être améliorés. Le système Rankine doit quand à lui être testé sur un camion prototype pour pouvoir véritablement estimer son potentiel final.

Mots clés: récupération d'énergie, cycle de Rankine, générateur thermoélectrique, véhicule industriel, camion, modélisation.

Contents

General introduction

On current diesel engines, a high amount of energy is lost as heat to the ambient. With current oil price increasing trends, new solutions are being developed to further improve fuel efficiency of current truck powertrain solutions. Waste heat recovery systems (WHRS) are possible solutions that need to be studied and analyzed for the long haul truck application. They can convert the high amount of heat wasted in exhaust gases into usable energy (mechanical energy or electrical energy) that will not be supplied by the main diesel engine, thus saving fuel.

This thesis work focuses on two waste heat recovery systems: the Rankine heat engine and the thermoelectric generator that are considered as two promising ways to further recover heat and make a step in truck powertrain fuel consumption improvement.

This industrial PhD is done within the guidance of Renault truck SAS (the french Volvo group joint company), the applied thermodynamic laboratory of the university of Liège and the Jean-Lamour Institute of the Mines of Nancy School.

This document does not intend to be comprehensive as it is a huge task to study two waste heat recovery systems.

The main objective of this thesis work is first to understand how such waste heat recovery systems could be implemented under current truck constraints, what would be their predicted performance if implemented, and understand how physical limitations affect the performance of those systems by means of first modeling studies and first experimental tests done within the research programs.

As a result, this thesis work has been divided into five main chapters as illustrated in the schematic shown in figure 1.

The first chapter will briefly remind the context of the study and why waste heat recovery appears as a promising path to further enhance fuel economy. It will remind principles of the Rankine heat engines and thermoelectric generators as well as address the main literature found on these fields.

The second chapter will review truck constraints to better understand what are boundary limitations of the truck but also give considerations to waste heat recovery architectures that are possible and the one chosen for the study.

Chapter 3 will then focus on the modeling. From simple modeling to complex ones, it defines how calculation results from chapter 4 and 5 were obtained and what were the main assumptions. It is guessed that this work will be completed in the future as lots of assumptions have not been validated due to time constraints.

Chapter 4 studies a particular thermoelectric generator that was built under the french Renoter research program. It is analyzed by means of a software developed under the program and conclusions are drawn on limitations of the thermoelectric generator technology.

Finally, chapter 5 discusses the Rankine heat system from pure thermodynamic studies results to a more complex GT-power model with component partial validations done under the french TIGRE research program. The Rankine heat engine design done within the company will be also addressed with its unknowns.

The general conclusion gives the status of waste heat recovery system as well as possible next steps and further studies that could be done in the future.

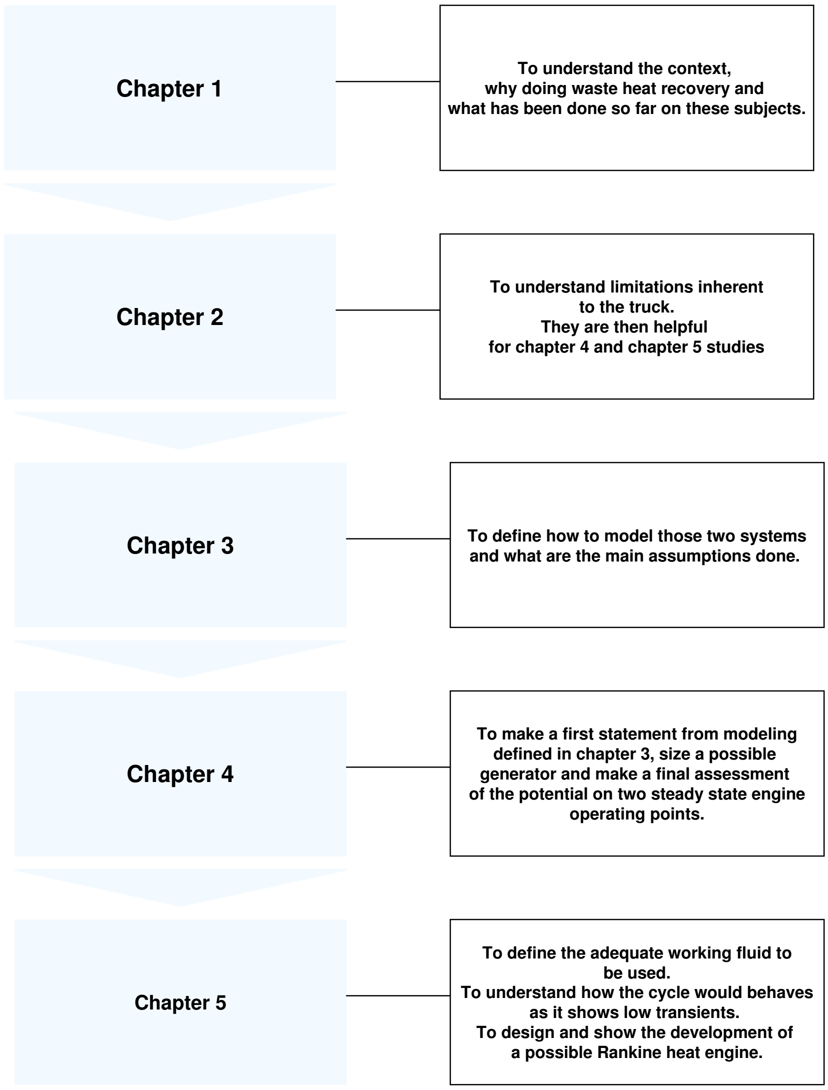

Figure 1: Schematic representation of how this thesis work is organized.

Bibliography

[1] New minto's unique steamless "steam" car, October 1970.

[2] Metal price and news, available online at http://www.metalprices.com, 2010.

[3] L. Aixala and V. Monnet. Renoter projectl: waste heat recovery on passenger car and heavy-duty truck diesel engine thanks to thermoelectricity. In *IAV 2010 conference, thermoelectric goes automotive.*, 2010.

[4] G. Angelino and P.C. di Paliano. Organic rankine cycles (orcs) for energy recovery from molten carbonate fuel cells. In *Energy Conversion Engineering Conference and Exhibit, (IECEC) 35th Intersociety*, volume vol°2, pages pp1400–1409. IEEE, 2000.

[5] G. Angelino and C. Invernizzi. Experimental investigation on the thermal stability of some new zero odp refrigerants. *International Journal of Refrigeration*, 26(1):51 – 58, 2003.

[6] Bernard Aoun. *Micro-combined heat and power operating on renewable energy for residential building.* PhD thesis, Mines of Paris school, 2008.

[7] v2B (1996) Aztech Software, Melcor.

[8] K. Azzouz and M. Simonin. Contact tube/ailette. October 6th 2010.

[9] Badr et al. Expansion machine for a low power output steam rankine cycle engine. *Applied Energy*, 39:93–116, 1991.

[10] Y. Balloul. Demo software v2.2.b. 2011.

[11] Bass et al. Performance of the 1 kw thermoelectric generator for diesel engines. In *International conference on thermoelectrics*, Kansas city, 1994.

[12] L. E. Bell and J. W. Lagrandeur. Automotive waste heat conversion to power program. In *2010 vehicle technologies program annual merit review*, 2010.

[13] Di Bella et al. Laboratory and on highway testing of diesel organic rankine compound long-haul vehicle engine. *Power boosting : international congress*, 1983.

[14] J. Berjklie and S. Luchter. Rankine cycle working fluid selection and specification rationale. *Society of Automotive Engineers (SAE)*, 690063:661–667, 1969.

[15] H. Borg. Volvo engineering report : Power balance test no. 1 has been conducted according to tc313 on p3471 pnlt 520 hp series c engine. Technical report, Volvo Powertrain, 2010.

[16] J. Braly and R. Roussel. Waste heat recovery by rankine, cooling. Results for the higher condenser, mass flow rate of 2.8 kg/s, April 2011.

[17] Caillat et al. Development of high efficiency segmented thermoelectric unicouples. In *International conference on thermoelectrics*, 2001.

[18] Chakraborty et al. Thermodynamic modelling of a solid state thermoelectric cooling device: Temperature-entropy analysis. *International Journal of Heat and Mass Transfer*, 49(19-20):3547 – 3554, 2006.

[19] CITEPA. Rapport national d'inventaire pour la france au titre de la convention cadre des nations unies sur les changements climatiques et du protocole de kyoto. Technical report, CITEPA, 2010.

[20] CNR. Indice synthétique des longues distances (40 tonnes), 2009.

[21] Crane et al. Modeling the building blocks of a 10thermoelectric power generator. In *International Conference on Thermoelectrics n° 27, Corvallis*, volume 38, pages 1382–1386, 2009.

[22] D. Crane. Status of segmented element thermoelectric generator for vehicle waste heat recovery. In *Thermoelectric application workshop, San-Diego*, 2011.

[23] D. T. Crane. *Optimizing thermoelectric waste heat recovery from an automotive cooling system.* PhD thesis, University of Maryland, 2003.

[24] Cuevas et al. Development and validation of a condenser three zones model. *Journal of Applied Thermal Engineering*, 29:3542–3551, 2009.

[25] H.M. Curran. Use of organic working fluids in rankine engines. *Journal of Energy*, vol°5:pp218–223, 1981.

[26] C. De-Vaulx. Rapport d'essai n°3. Technical report, CRISMAT, 2009.

[27] C. De-Vaulx. High temperature thermoelectric power generator test bench. Technical report, CRISMAT, 2011.

[28] C. De-Vaulx. Réunion de suivi renoter n°20. Oral presentation, april,14th 2011.

[29] Declaye et al. Evaluation du potentiel de récupération d'énergie à l'échappement d'un moteur tdi à l'aide d'un cycle de rankine organique (orc). In *Actes des Congrès Français de Thermique: Energies et Transports Durables*, 2010.

[30] Cédric DeVaulx. Générateurs thermoélectriques pour applications automobiles - rapport bibliographique. Technical report, Renoter project, 2009.

[31] D. Didiot and N. Espinosa. Primitive evaporator modeling under gt-power. Technical report, Internal Report (Volvo), 2009.

[32] D. C. Dinescu and M. Tazerout. Mean value modeling of a variable nozzle turbocharger (vnt). *UPB Scientific bulleting*, 72:Iss.1, 2010.

[33] Dong et al. Heat transfer and pressure drop correlations for the multi-louvered fin compact heat exchangers. *Energy Conversion and Management*, 48(5):1506–1515, 2007.

[34] Doyle et al. Installation of a diesel-organic rankine compound engine in a class 8 truck for a single-vehicle test. *Society of Automotive Engineers (SAE)*, 790646, 1979.

[35] N. Dronniou. *Etude théorique et expérimentale des stratégies de combustion homogène. Application aux moteurs Diesel pour véhicules industriels.* PhD thesis, Université d'Orléans, 2008.

[36] A. Duparchy. Device for controlling the working fluid circulating in a closed circuit operating according to a rankien cycle and method of using same device, May 2010. US Patent App. 12/775,508.

[37] R. El Chammas and D. Clodic. Combined cycle for hybrid vehicles. *SAE Technical Paper*, pages 01–1171, 2005.

[38] Espinosa et al. Modeling a thermoelectric generator applied to diesel automotive waste heat recovery. *Journal of electronic materials*, 9:1446–1455, 2009.

[39] Espinosa et al. Rankine cycle for waste heat recovery on commercial trucks. In *The 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. SIA, 2010.

[40] Espinosa et al. Transient organic rankine cycle modelling for waste heat recovery on a truck. In *ECOS*, 2011.

[41] N. Espinosa. Rankine cycle for waste heat recovery - litterature survey. Technical report, Volvo Engineering Report, 2009.

[42] L. Fernando Almeida Fontenele. Advanced engineering - litterature survey, supplier contacts and simulations about auxiliarie's electrification. Technical report, Volvo Engineering Report, 2010.

[43] G. Fraisse, M. Lazard, C. Goupil, and JY Serrat. Study of a thermoelement's behaviour through a modelling based on electrical analogy. *International Journal of Heat and Mass Transfer*, 53(17-18):3503–3512, 2010.

[44] Freymann et al. The turbosteamer : a system introducing the principle of cogeneration in automotive applications. *MTZ*, 69:20–27, 2008.

[45] Gaillard et al. The new renault trucks euro iii / iv dxi 11 engine. In *Diesel Engine - May 31 & June 1,*, 2006.

[46] L. Gay. *Modélisation d'une machine frigorifique fonctionnant au R407C en régime transitoire*. PhD thesis, INSA de Lyon, 1999.

[47] S. Ghamaty and N. Elsner. Si / sige quantum well thermoelectric materials and devices for waste heat recovery from vehicles and industrial plants. In *International Symposium on nano-thermoelectrics, Osaka, Japan*, 2007.

[48] Gu et al. Theoretical and experimental investigation of an organic rankine cycle for a waste heat recovery system. *Journal of Power and Energy*, 223, Part A, 2009.

[49] I. Guitari. *Etude expérimentale et modélisation d'une pompe à chaleur fonctionnant au CO2*. PhD thesis, INSA de Lyon, 2005.

[50] Robert. R. Heikes and Roland. W. Ure. *Thermoelectricity: science and engineering*. Interscience, 1961.

[51] T. Holmqvist. Air flow measurements in vfl performed in the advanced engineering project chgt5 "alternative placement of heat exchangers". a roof and a sun visor basic configuration are investigated. Technical report, Volvo engineering report, 2006.

[52] Hountalas et al. Study of available exhaust gas heat recovery technologies for hd diesel engine applications. *International Journal Alternative Propulsion*, 1, 2007.

[53] Hung et al. A review of organic rankine cycles (orcs) for the recovery of low-grade waste heat. *Energy*, 22:661–667, 1997.

[54] T.C. Hung. Waste heat recovery of organic rankine cycle using dry fluids. *Energy Conversion and Management*, 42:539–553, 2001.

[55] Ibaraki et al. Study of efficient on-board waste heat recovery system using rankine cycle. *Review of Automotive Engineers*, 28:307–313, 2007.

[56] IEA. End-use petroleum product prices and average crude oil import costs april 2010. http://www.iea.org/stats/surveys/mps.pdf, 2010.

[57] Invernizzi et al. Bottoming micro-rankine cycles for micro-gas turbines. *Applied Thermal Engineering*, 27:100–110, 2007.

[58] C.M. Jaworski. Opportunities for thermoelectric energy conversion in hybrid vehicles. Master's thesis, Ohio State University, 2007.

[59] Junqi et al. Heat transfer and pressure drop correlations for the wavy fin and flat tube heat exchangers. *Applied thermal engineering*, 27:2066–2073, 2007.

[60] T. Kajikawa. Approach to the practical use of thermoelectric power generation. volume 38, pages 1083–1088. Springer, 2009.

[61] Kane et al. Small hybrid solar power system. *Energy*, 29:1427–1443, 2003.

[62] W.M. Kays and A. L. London. *Compact heat exchangers third edition*. Krieger, 1998.

[63] A. Kellström. Volvo internal presentation : Emission regulation charts. on-road (automotive). april 2007.

[64] H. Kleinke. New bulk materials for thermoelectric power generation: clathrates and complex antimonides. *Chemical Materials*, 22:604–611, 2010.

[65] V.V. Klimenko. A generalized correlation for two-phase forced flow heat transfer. *International Journal of Heat and Mass Transfer*, 31:541–552, 1988.

[66] V.V. Klimenko. A generalized correlation for two-phase forced flow heat transfer - second assessment. *International Journal of Heat and Mass Transfer*, 33:2073–2088, 1990.

[67] R. W. Kruiswyk and D. M. Milam. Deer conference : Engine system approach to exhaust energy recovery. 2006.

[68] A. Larnaud. Er n°534006 : waste heat recovery - rankine fluid choice. Technical report, Volvo Engineering Reports, 2010.

[69] Alain Laville. Volvo presentation: récupération d'énergie à l'échappement. renoter. First cooling investigation on a Euro 5 premium truck., 2009.

[70] Lazard et al. Some considerations about the thermal analysis of a thermoelectric leg. In *6th European Conference on Thermoelectrics, Paris*, 2008.

[71] M. Lazard. Heat transfer in thermo-electricity: Modelling, optimization and design. 9:129–134, 2009.

[72] J. Lebrun and V. Lemort. Machines et systèmes thermiques : notes de cours, université de liège. 2000.

[73] M. Lejeune. Volvo internal presentation : "tech event fuel economy, reflexion on morning session and afternoon session introduction.", June 2010.

[74] Lemort et al. Development and experimental validation of an organic rankine cycle model. In *Heat SET 2007 : Heat transfer in components and systems for sustainable energy technologies*, 2007.

[75] Lemort et al. Experimental characterization of a hermetic scroll expander for use in a micro-scale rankine cycle. *Journal of Power and Energy*, Proceedings of the Institution of Mechanical Engineers, Part A, 2011.

[76] V. Lemort. *Contribution to the Characterization of Scroll Machines in Compressor and Expander Modes*. PhD thesis, University of Liège, 2008.

[77] Liu et al. Effect of working fluids on organic rankine cycle for waste heat recovery. *Energy*, 29:1207–1217, 2004.

[78] V. Maizza and A. Maizza. Working fluids in non-steady flows for waste energy recovery systems. *Applied Thermal Engineering*, 16:579–590, 1996.

[79] A.C. Mcmahan. *Design and Optimization of Organic Rankine Cycle Solar-Thermal Powerplants.* PhD thesis, University of Wisconsin-Madison, 2006.

[80] G.P. Meisner. Develop thermoelectric technology for automotive waste heat recovery. In *2010 vehicle technologies program annual merit review.*, 2010.

[81] C. Nelson. Waste heat recovery. In *DEER Conference*, 2008.

[82] C. Nelson. Exhaust energy recovery. In *Mid-year review DEER conference.*, 2010.

[83] B. Obama. Presidential memorandum regarding fuel efficiency standards. Memorandum, May 2010.

[84] Office of Transportation and Air Quality. Epa and nhtsa propose first-ever program to reduce greenhouse gas emissions and improve fuel efficiency of medium and heavy-duty vehicles: regulatory annoucement, October 2010.

[85] J. G. Owens. Low gwp alternatives to hfcs and pfcs. 3M Specialty Materials, 2010.

[86] J.N. Paquien. Engineering report : Note de synthèse sur les ressources et prix du tellure - version 2 - juin 2010. Technical report, Materials Technology - Volvo, 2010.

[87] P. S. Patel and E. F. Doyle. Compounding the truck diesel engine with an organic rankine cycle system. *Society of Automotive Engineers (SAE)*, 760343, 1976.

[88] Quoilin et al. Expansion machine and fluid selection for the organic rankine cycle. In *7th international conference on heat transffer, fluid mechanics and thermodynamics, 19-21 july 2010, Antalya, Turkey*, 2010.

[89] Quoilin et al. Dynamic modeling and optimal control strategy of waste heat recovery organic rankine cycles. *Applied Energy*, 88(6):2183 – 2190, 2011.

[90] S. Quoilin. Experimental study and modelling of a low temperature rankine cycle for small scale cogeneration. Master's thesis, University of Liège, 2007.

[91] M. Reck and D. Randolf. An organic rankine cycle engine for a 25 passenger bus. *Society of Automotive Engineers (SAE)*, 730219, 1973.

[92] T. Reiche. Er n°534004 : the waste heat recovery potential of different secondary thermodynamic cycle models. Technical report, Volvo Engineering Report, 2009.

[93] T. Reiche. Litterature survey on expanders for waste heat recovery rankine cycles. Technical report, Volvo Engineering Report, 2009.

[94] R. Revellin. *Experimental two-phase fluid flow in microchannels*. PhD thesis, École Polytechnique Fédérale de Lausanne, 2006.

[95] D.M. Rowe. *CRC Handbook of Thermoelectrics*. CRC Press, 1995.

[96] Saleh et al. Working fluids for low temperature organic rankine cycles. *Energy*, 32:1210–1221, 2007.

[97] Saqr et al. Thermal design of automobile exhaust based thermoelectric generators: objectives and challenges. *International Journal of Automotive Technology*, 9:155–160, 2008.

[98] P. Schalbart. *Modélisation du fonctionnement en régime dynamique d'une machine frigorifique bi-étagée à turbo-compresseurs - application à sa régulation*. PhD thesis, INSA de Lyon, 2006.

[99] Schock et al. Thermoelectric conversion of waste heat to electricity in an ic engine powered vehicle. In *2010 vehicle technologies program annual merit review*, 2010.

[100] Schwentker et al. A simulation and design tool for flat tubes louvered-fin heat exchangers. *Society of Automotive Engineers*, 2006-01-1451, 2006.

[101] R. K. Shah. Advances in automotive heat exchanger technology. *Society of Automotive Engineers*, 2003-01-0533, 2003.

[102] R. K. Shah and D.P. Sekulic. *Fundamentals of heat exchanger design*. John Wiley & Sons, 2003.

[103] Shi et al. Thermoelectric properties of n-type and multiple-filled skutterudites. *Journal of electronic materials*, vol.38:special issue paper n°7, 2009.

[104] M. Simonin. Device for generating electrical energy, heat exchange bundle comprising such a device, and heat exchanger comprising such a bundle, December 30 2009. WO Patent WO/2009/156,361.

[105] Smith et al. Power recovery from low cost two-phase expanders. 1999.

[106] K.D. Smith. An investigation into the viability of heat sources for thermoelectric power generation system. Master's thesis, Rochester Institute of Technology, 2009.

[107] G. J. Snyder and E. S. Toberer. Complex thermoelectric materials. *Nature materials*, 7, 2008.

[108] G.J. Snyder and T. Caillat. Using the compatibility factor to design high efficiency segmented thermoelectric generators.

[109] M. Sorazawa. Fuel economy simulation of series hybrid utilizing thermoelectric heat recovery system. In *IAV second international conference - Berlin*, December 2010.

[110] R. Stobart and R. Weerasinghe. Heat recovery and bottoming cycles for si and ci engines - a perspective. *Society of Automotive Engineers*, 2006-01-0662, 2006.

[111] Tardy et al. Volvo engineering report - optifuel lab - demo truck : Fuel economy results. Technical report, Volvo 3P, 2009.

[112] Tchanche et al. Economic optimization of small scale organic rankine cycles. In *10th Biennial Conference on Engineering Systems Design and Analysis, Istanbul, ASME 2010*, 2010.

[113] TECO. Feasibility test on compounding the internal combustion engine for automotive vehicles, task ii. Technical report, Thermo Electron Corporation, 1976.

[114] Teng et al. Achieving high engine efficiency for heavy-duty diesel engines by waste heat recovery using supercritical organic-fluid rankine cycle. *Society of Automotive Engineers*, 2006-01-3522, 2006.

[115] Teng et al. Waste heat recovery of heavy-duty diesel engines by organic rankine cycle part 1 : hybrid energy system of diesel and rankine engines. *Society of Automotive Engineers*, 2007-01-537, 2007.

[116] Thatcher et al. Testing of an automobile exhaust thermoelectric generator in a light truck. *Journal of Automobile Engineering*, 221:95–107, 2007.

[117] J.R. Thome. *Engineering databook III*. Wolverine Tube Inc, 2008.

[118] L. Tilman. Condenser of en exhaust heat recovery rankine cycle. Technical report, Volvo Engineering Report, 2009.

[119] L. Tilman. Packaging study and dynamic modeling of an automotive waste heat recovery rankine cycle. Master's thesis, University of Liège, 2010.

[120] unknown. http://www.pump-zone.com/compressors/compressors/flow-simulation-in-pumpcompressor-design.html, 2011.

[121] I. Vaja. *Definition of an object oriented library for the dynamic simulation of advanced energy systems : methodologies, tools and application to combined ICE-ORC power plants*. PhD thesis, Parma university, 2009.

[122] Vasquez et al. State of the art of thermoelectric generators based on heat recovered from the exhaust gases of automobiles. In *Proceedings of the 7th European workshop on thermoelectrics, Pamplona, Spain*, 2004.

[123] J. Wall. The right technology matters, the importance of public-private partnerships for engine technology development. In *2009 Directions in Engine-Efficiency and Emissions Research (DEER) Conference Presentations.*, 2009.

[124] HiZ website. Properties, 2010.

[125] Wei et al. Performance analysis and optimization of organic rankine cycle (orc) for waste heat recovery. *Energy Conversion and Management*, 48:1113–1119, 2007.

[126] Winandy et al. Modelling of an air condenser working in critical zone for engine cooling by refrigeration loop. *British library, The world's knowledge*, 2003.

[127] Yamamoto et al. Design and testing of the organic rankine cycle. *Energy*, 26:239–251, 2001.