

Study of flow energy merger of hybrid pneumatic power system

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ABSTRACT

Social problems such as environmental pollution and limited crude oil resources are great challenges that have become major concerns, so scientists and researchers are investing significant time and effort in developing new technologies that can be applied in the automobile industry. The focus of these technologies is the realization of zero-pollution and green vehicles, including the creation of hybrid electric vehicles (HEVs), electric vehicles (EVs), fuel cell vehicles (FCVs). HEV, EV, and FCV technologies have been further developed and are now in limited use. However, these vehicles still have limitations. In order to solve the above limitations, a hybrid pneumatic power system (HPPS) is proposed in this study. This system stores the flow energy instead of a battery's electrochemical energy; moreover, it can recycle the exhaust-gas energy of an internal combustion engine (ICE) and make the ICE operate at its sweet spot of maximum efficiency. Therefore, it can be considered as an effective solution to significantly increase system energy efficiency and effectively improve exhaust emissions. This study focuses mainly on achieving two objectives. First, it experimentally investigates the operating capabilities of the HPPS, effects of the Pair, and contraction of section area (CSA) at the merging region on the flow energy merger in the system. Second, this study also investigates the effects of the dimensions of merger pipe, compressed airflow rate, and CSA on the exhaust-gas energy recycling, and determines the optimum dimensions and suitable adjustment of the CSA for the best merging process by using three-dimensional simulation of the computational fluid dynamic (CFD). The experiments and simulation were performed on a HPPS that used an innovative energy merger pipe where configuration and dimensions were suitably designed, while CSA was adjusted for the change in Pair and compressed airflow rate. The obtained results indicate that the exhaust-gas energy recycling and merger flow energy in the HPPS not only strongly depend on configuration and dimensions of the energy merger pipe but also are significantly influenced by CSA adjustment for the change in Pair and compressed airflow rate. These study results will be valuable bases and useful to research and design the energy merger pipe and control system of the HPPS.

Keywords : Hybrid pneumatic power system ; Exhaust-gas energy ; Energy merger pipe ; Flow energy merger

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REFERENCES

- [1] W.W. Pulkrabek. Engineering Fundamentals of the Internal Combustion Engine. Second Edition, USA, 2004, by Pearson Prentice-Hall, Pearson Education, Inc, Upper Saddle River, NJ 07458.
- [2] C. Davis, B. Edelstein, B. Evenson, A. Brecher, D. Cox. Hydrogen Fuel Cell Vehicle Study. Report Prepared for the Panel on Public Affairs (POPA), Ameican Physical Society. USA, Jun. 12, 2003.
- [3] N. Iwai. Analysis on fuel economy and advanced systems of hybrid vehicles. JSAE Review 20 1999; 20: 3?{11.
- [4] J.V. Mierlo, G. Maggetto, Ph. Lataire. Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles. Energy Conversion and Management 2006; 47: 2748?{2760.
- [5] Toyota Co. Worldwide Prius Sales Top 1 Million Mark. Available from: <http://www.toyota.co.jp/en/news/08/0515.pdf>.
- [6] M. Granovskii, I. Dincer, M.A. Rosen. Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles. J. Power Sources 2006; 159: 86?{93.
- [7] I. Dincer. Environmental and sustainability aspects of hydrogen and fuel cell systems. International Journal of Energy Research 2007; 31: 29?{55.
- [8] M.M. Hussain, I. Dincer, X. Li. A preliminary life cycle assessment of PEM fuel cell powered automobiles. Applied Thermal Engineering 2007; 27: 94?{99.
- [9] K. Morita. Automotive power source in 21st century. JSAE Review 2003; 24: 3 – 7.
- [10] R. Priddle. Automotive fuels for the future. 21th International Energy Agency, 1999, IEA – AMF advanced motor fuels.
- [11] M.J. Kellaway. Hybrid buses-What their batteries really need to do. J. Power Sources 2007; 186: 95?{98.
- [12] H. Tsuchiya. Innovative renewable energy solutions for hydrogen vehicles. International Journal of Energy Research 2008; 32: 427?{435.
- [13] F. Barbir, S. Yazici. Status and development of PEM fuel cell technology. International Journal of Energy Research 2008; 32: 369?{378.
- [14] A. Emadi, S.S. Williamson. Fuel Cell Vehicles: Opportunities and Challenges. Power Engineering Society General Meeting, 2004. IEEE, vol. 2, pp. 1640?{1645, June 2004.
- [15] Moteur Development International (MDI). Availabel from: <http://www.theaircar.com/>.
- [16] C. Knowlen, A.T. Mattick, H. Deparis, A. Hertzberg. Quasi-isothermal expansion engines for liquid nitrogen automotive propulsion. SAE Paper No. 972649; 1997.

- [17] C. Knowlen, A.T. Mattick, A.P. Bruckner, A. Hertzberg. High-efficiency energy-conversion systems for liquid-nitrogen automobiles. SAE Paper No. 981898; 1998.
- [18] M.C. Plummer, C.A. Ordonez, R.F. Reidy. Liquid nitrogen as a non-polluting vehicle fuel. Society of Automotive Engineers, SAE Paper 01-2517; 1999.
- [19] C.A. Ordonez. Liquid nitrogen fueled, closed Brayton cycle cryogenic heat engine. *Energy Conversion and Management* 2000; 41: 331-341.
- [20] S. Lemoufouet, A. Rufer. Hybrid Energy Storage Systems based on Compressed Air and Super-capacitors with Maximum Efficiency Point Tracking. EPE 2005, ISBN: 90-75815-08-5.
- [21] K.D. Huang, S.C. Tzeng. Development of a hybrid pneumatic power vehicle. *Applied Energy* 2005; 80: 47-59.
- [22] K.D. Huang, S.C. Tzeng, W.P. Ma, W.C. Chang. Hybrid pneumatic power system which recycles exhaust-gas of an internal combustion engine. *Applied Energy* 2005; 82: 17-32.
- [23] K.D. Huang, S.C. Tzeng, W.C. Chang. Energy saving hybrid vehicle using a pneumatic power system. *Applied Energy* 2005; 81: 1-18.
- [24] K.D. Huang, K.V. Quang, S.H. Wei, T.C. Liu, K.T. Tseng, Y.W. Tsai. Study of an innovative hybrid pneumatic power system. Fourth International Conference on Flow Dynamics, Sep. 26-28, 2007, Sendai, Miyagi, Japan.
- [25] K.D. Huang, K.V. Quang, N.H. Nam, T.C. Liu, C.H. Lin. Study of flow energy merging capability of hybrid pneumatic power system. 25th National Conference on Mechanical Engineering of CSME. Nov. 21-22, 2008, Dayeh, Changhua, Taiwan.
- [26] K.D. Huang, K.V. Quang, K.T. Tseng. Study of recycling exhaust gas energy of hybrid pneumatic power system with CFD. *Energy Conversion and Management* 2009; 50: 1271-1278.
- [27] K.D. Huang, K.V. Quang, N.H. Nam, C.H. Lin. Improvement of exhaust-gas energy recycling in hybrid pneumatic power system by an innovative energy merger pipe. 20th international symposium on transport phenomena ISTP-20, Jul. 7-10, 2009, Victoria, Canada.
- [28] R.V. Basshuysen, F. Schafer. Internal Combustion Engine handbook, Basics, Components, Systems, and Perspectives. SAE Order No. R-345, Canada, ISBN 0-7680-1139-6.
- [29] FU SHENG GROUP. A-series, air-cooled heavy-duty reciprocating air compressor. Available from: http://www.fusheng.com/machinery/products/series_a.htm.
- [30] D.E. Winterbone, R.J. Pearson. Theory of Engine Manifold Design Wave Action Methods for Internal Combustion Engine. Professional Engineering Publishing Limited London and Bury St Edmunds, UK, ISBN 1 86058 209 5.
- [31] M.J. Zucrow. Principles of Jet Propulsion and Gas Turbines. Printed in the United States of America – 1954.
- [32] K.D. Huang, N.H. Nam, K.V. Quang. Validation of dynamic model of hybrid pneumatic power system. SAE paper No. 2009-01-1304.
- [33] K.V. Quang. Simulation of the thermodynamic cycle and mass flow in scavenge process of ICE using AVL Boost. Master of science Thesis, Hanoi University of Technology, Hanoi, 2002.
- [34] AVL, Thermodynamic cycle simulation Boost. Boost user 's guide, Version 4.0.4, Jun. 2004.
- [35] R.E. Sonntag, C. Borgnakke, G.J. Van Wylen. Fundamentals of thermodynamics. Sixth edition, Printed in the United States of America, ISBN 0-471-15232-3.
- [36] N.T. Tien. Principle of Internal Combustion Engine. Educational Publishing House, Hanoi, 2003.
- [37] K.D. Huang, K.V. Quang, Y.Y. Wu, K.T. Tseng. Energy merger pipe optimization of hybrid pneumatic power system by using CFD. The First International Conference on Applied Energy (ICAE09), Jan. 5-7, 2009, Hong Kong.
- [38] K.D. Huang, K.V. Quang, K.T. Tseng. Study of the effect of contraction of cross-sectional area on flow energy merger in hybrid pneumatic power system. *Applied Energy* 2009; 86: 2171-2182.
- [39] K.D. Huang, K.V. Quang, K.T. Tseng. Experimental study of exhaust-gas energy recycling efficiency of hybrid pneumatic power system. *International Journal of Energy Research* 2009; 33: 931-942.
- [40] K.D. Huang, K.V. Quang, K.T. Tseng. Experimental study of flow energy merger of hybrid pneumatic power system. IEEE International Conference on Sustainable Energy Technologies (ICSET 2008), Nov. 24-29, 2008, Singapore.
- [41] FLUENT 6.3, 2006: User guide, all volumes; Fluent Inc. Lebanon, Jun. 2006.
- [42] Gambit 2.2, 2001: User 's guide; Fluent Inc. Lebanon, Dec. 2001.