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A novel second-order thermal model of Stirling engines with consideration of losses due to the speed of the crack system



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ABSTRACT

Very accurate second-order thermal models have been developed for the thermal simulation of Stirling engines in recent years. One of the last ones is the comprehensive polytropic model of Stirling engine called the CPMS model. The accuracy of the CPMS model was found to be sufficient for the nominal operation of a prototype Stirling engine known as the GPU-3 engine. Nevertheless, the accuracy of the CPMS model was drastically reduced at high rotational speeds of the engine. In this paper, power loss and pressure change due to the inertial force of the crank system were integrated into the CPMS thermal model in order to compensate inaccuracy of the CPMS model at high rotational speeds. Moreover, the effect of rotational speed on the gas temperature in heater and cooler was also incorporated. A precise model for evaluating the mechanical friction loss was also employed and compared with the simple frictional model of the simple frictional model used in the CPMS. The model was examined on the GPU-3 engine, and it was found that it has superior accuracy compared to the previous thermal model over the entire working regime of the GPU-3 engine.

1. Introduction

The Stirling engine is a type of external heat engine that can be used to generate power from the thermal energy from various sources from fossil fuels to renewable heat sources such as the solar energy. On the other hand, it has the advantage of quieter operation compared to internal-combustion engines. On the other hand, it could be used in the reverse cycle as the Stirling cooler or refrigerator. Due to these advantages, Stirling systems are suitable alternatives for power generation and refrigeration in various application. For the proper design of Stirling engines/coolers, accurate thermal models that are able to predict the thermal performance of Stirling engines is required. First-order analytical model [1-5], second-order numerical models [6-13], and third-order models [14-19] are usually employed for this purpose. The first-order or closed-form models are those models that can easily estimate thermal performance of Stirling engine based on the operating parameters; however, they usually suffer from lack of enough accuracies required by designers. On the other hand, those are usually developed for Stirling cycles, not Stirling engines and coolers; therefore, those cannot be used to study the effect of engines/cooler's parameters. For accurate simulation of Stirling engines/coolers, numerical secondorder and third-order models are used. The third-order models [14-19] are numerical models that are developed based on the computational

fluid dynamics, CFD. Third-order models suffer from some limitation, including the high computational cost and the lack of generality that makes it impossible to be used to simulate every type of the engine. Instead, the third-order models should be developed for a specific type of engine, and the results cannot be extended to other engines. The second-order models are numerical zero-dimensional models that have sufficient accuracy for most cases. Moreover, they can be easily applied to various Stirling engines. In other words, second-order models can be utilized to simulate every type of Stirling engines/coolers with reasonable accuracy. On the other hand, due to much lower computation time compared to third-order models, these models can be used easily for design and optimization purpose. In second-order models, the engine is divided into the five compartments and governing equations of energy and mass are applied for each compartment as a function of the rotational angle of the crank system (time) while the spatial dependence of governing equations is ignored. Therefore, these models are also called as the zero-dimensional models. It means that the governing equations are not dependent on any coordinate. In these models, a system of boundary value ordinary differential equation, ODE, with respect to the crank angle (time) is obtained and converted into an initial value problem. Consequently, they are solved using the fourth order Runge-Kutta method. An early second order model was developed by the Urieli and Berchowitz [6] considering adiabatic expansion/

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| $ \begin{array}{c} c_{p} & \text{polytropic specific heat (k) kg^{-1} K^{-1}) & c & \text{compression space} \\ c_{p} & \text{specific heat at constant volume (kJ kg^{-1} K^{-1}) & c & \text{compression space} \\ c_{p} & \text{specific heat at constant volume (kJ kg^{-1} K^{-1}) & c & \text{crank-case} \\ \hline \\ d & \text{differential of a parameter or dimeter (m) & ck & \text{compression cooler space interface} \\ e & \text{the eccentricity of the crank system (m) } & cp & \text{crank-pin bearing shell} \\ \hline \\ r & \text{rotation frequency of engine (Hz) } & d & \text{displacer} \\ f_{m} & \text{constants values } & e & \text{expansion space interface} \\ \hline \\ f_{m} & \text{constants values } & e & \text{expansion space} \\ f_{m} & \text{constants values } & f & \text{friction} \\ f_{m} & \text{mass moment of inertia (kg m^{2}) } & h & \text{heater} \\ \hline \\ i & \text{gas moment of inertia (kg m^{2}) } & h & \text{heater} \\ f_{m} & \text{mass moment of inertia (kg m^{2}) } & h & \text{heater} \\ f_{m} & \text{gas conductivity} & \text{ind} & \text{indicated} \\ K_{s} & \text{specific heat at iol } (C_{y}/C_{y}) & k & \text{cooler (kooler)} \\ L & \text{length (m)} & Kr & \text{cooler (kooler)} \\ K & \text{gas conductivity} & \text{ind} & \text{indicated} \\ K_{s} & \text{specific heat ratio } (C_{y}/C_{y}) & k & \text{cooler (kooler)} \\ R & \text{mass of a component of the crank system (kg) } & m & \text{mechanical} \\ R & \text{mass of a component of the crank system (kg) } & m & \text{mechanical} \\ R & \text{the rotation speed of the engine (rpm)} & ma & \text{effect of inertial force of mass (m) at the rotational fre- quere (w^{2}) \\ P_{s} & \text{presure } (k^{2}) & K & \text{cooler twoler from contants values } \\ R & \text{universal gas constant (kJ/Kg K)} & R & \text{transfer twoles } \\ R & \text{universal system (kl)} & R & \text{regenerator } \\ R & \text{universal system (kl)} & R & \text{regenerator } \\ R & \text{universal system (kl)} & R & \text{transfer twoles } \\ R & \text{universal system (kl)} & R & \text{cooler twole interface } \\ R & \text{universal system (kl)} & R & \text{regenerator } \\ R & \text{universal system (kl)} & R & \text{cooler twole interface } \\ R & \text{universal system (kl)} & R & \text{cooler twole interface } \\ R & \text{universal system (kl)} &$ | $D_1,, D_n$ | the average speed of molecules $(m s^{-1})$ | σασσειφι | |
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| $ \begin{array}{c} c_{p} & \text{spectra i at constant volume (U kg^{-1} K^{-1}) & c & confinets of space interface \\ p & diameter (m) & q & crank-journal \\ differential of a parameter or diameter (m) & q & crank-join \\ e & the eccentricity of the crank system (m) & q & crank-pin \\ f & rotation frequency of engine (Hz) & d & displacer \\ f_{m} & constants values & e & expansion space interface \\ f_{m},,G_{n} & constants values & e & expansion space interface \\ f_{m},,G_{n} & constants values & e & expansion space \\ H_{m},H_{n} & constants values & f & friction \\ f & gyration radius (m) & h & heater \\ i & gyration radius (m) & h & heater \\ i & gyration radius (m) & h & heater \\ k_{n} & specific heart at iology (C_{n}) & h \\ k_{n} & gas conductivity & ind \\ k_{n} & gas conductivity & ind \\ k_{n} & specific heart atio (C_{n}/C_{n}) & k \\ k_{n} & cooler (kooler) - regenerator interface \\ H & mass of a component of the crank system (kg) & m & mechanical \\ N_{n} & the tratio (C_{n}/C_{n}) & k & cooler (kooler) - regenerator interface \\ H & mass of the working (luid (kg) & leak & leakage \\ m & mass of a component of the crank system (kg) & m & mechanical \\ N_{n} & the trataion speed of the engine (rpm) & m & effect of inertial force of mass (m) at the rotational free \\ P_{n} & P_{n} & constant values & p & piston \\ P_{n} & P_{n} & constant values & p & piston \\ P_{n} & P_{n} & constant values & p & piston \\ P_{n} & P_{n} & constant values & p & piston \\ P_{n} & prace interface & m & m \\ R_{n} & universal gas constant (kJ/kg K) & Shuttle & shuttle effect \\ R_{n} & universal gas constant (kJ/kg K) & Shuttle & shuttle effect \\ R_{n} & universal gas constant (kJ/kg K) & Shuttle & shuttle effect \\ R_{n} & universal gas constant (kJ/kg K) & Shuttle & shuttle effect \\ R_{n} & universal gas constant (kJ/kg K) & Shuttle & shuttle effect \\ R_{n} & universal gas constant (kJ/kg K) & Shuttle & Shuttle & Store (K) & O convertational Fluid Dynamics \\ W_{n} & pover (kW) & QPW & Convertational Fluid Dynamics \\ W_{n} & pover (kW) & QPW & Conver$ | c_n | polytropic specific field (KJ Kg K) specific heat at constant processes $(k L k c^{-1} K^{-1})$ | U | |
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| $\begin{array}{llllllllllllllllllllllllllllllllllll$ | f _{re} | Reynolds friction factor | dc | displacer's connecting rod |
| $ \begin{array}{ll} H_{1,,H_{n}} & constants values & f & friction \\ I & mass moment of inertia (kg m2) & h & heater \\ i & gyration radius (m) & he & heater expansion space interface \\ J & the annular gap between piston and cylinder (m) and or ho hot gas so utput \\ moment of inertia (N m) & hi & hot gas output \\ k & gas conductivity & ind. indicated \\ k_g & specific heat ratio [C_p/C_v] & k & cooler (kooler) \\ L & length (m) & kr & cooler (kooler) \\ L & length (m) & kr & cooler (kooler) \\ R & mass of a component of the crank system (kg) & m & mechanical \\ N_r & the rotation speed of the engine (rpm) & m & effect of inertial force of mass (m) at the rotational frequency (a) \\ P_{b1,,P_{bm}} & constants values & p & piston \\ P & pressure (kPa) & pc & piston ^ s connecting rod \\ P & pressure (kPa) & pc & piston ^ s connecting rod \\ P & pradul number \\ Q & heat transfer (kJ) & r & r & regenerator heater interface \\ R & universal gas constant (kJ/kg K) & Shuttle shuttle effect \\ r & crank radius (m) & 0 & environment condition \\ Re & Reynolds number \\ T & temperature (K) or torque (N m) & wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & cooler wall \\ St & Stanton number \\ T & temperature (K) or torque (N m) & Wk & Cooler wall \\ St & Stanton number \\ T & temperature (K) & Or torque (N m) $ | $G_1,,G_n$ | constants values | е | expansion space |
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| kgas conductivityind.indicated k_g specific heat ratio $[C_p/C_v]$ kcooler (kooler)Llength (m)krcooler (kooler)-regenerator interfaceMmass of the working fluid (kg)leakleakagemmass of a component of the crank system (kg)mmechanicalNrthe rotation speed of the engine (rpm) $m\omega$ effect of inertial force of mass (m) at the rotational frequency (ω) P_{01} number of transfer unitsppistonPpressure (kPa)pcpiston's connecting rodPPrandtl numberpppiston-pinQheat transfer (kJ)rregeneratorquency (ω)shuttleshuttle effectRuniversal gas constant (kJ/kg K)ShuttleRuniversal gas constant (kJ/kg K)whRkcoler wallstroke (m)Sstroke (m)whMheater wallSstroke (m)CPDVvolume (K) or torque (N m)Abbreviationuthe velocity of as flow (m s ⁻¹)CPDComputational Fluid DynamicsWoutput work (kJ)GPUGround Power UnitVvolume (m ³)kWeKilonal power UnitVvolume (m ³)kWeKilonal power UnitKconduction resistance (m KW ⁻¹)ODEOrdinary Differential Equation x_p piston acceleration (m s ⁻²)PSVLPolytropic analysis of Stirling engine with Various Losses </td <td></td> <td>moment of inertia (N m)</td> <td>hi</td> <td>hot gas input</td> | | moment of inertia (N m) | hi | hot gas input |
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| $ \begin{array}{cccc} g_{h_1,\dots,q_{h_n}} & \mbox{constants values} & rh & \mbox{regenerator-heater interface} \\ r & \mbox{universal gas constant (kJ/kg K)} & Shuttle & shuttle effect \\ r & \mbox{crank radius (m)} & 0 & \mbox{environment condition} \\ Re & \mbox{Reynolds number} & wh & \mbox{heater wall} \\ S & \mbox{stroke (m)} & wk & \mbox{cooler wall} \\ St & \mbox{Stanton number} & \\ T & \mbox{temperature (K) or torque (N m)} & Abbreviation \\ u & \mbox{the velocity of gas flow (m s^{-1})} & \\ U_p & \mbox{or} \dot{x}_p & \mbox{the linear velocity of the piston (m s^{-1})} & CFD & \mbox{Comprehensive Polytropic Model of Stirling engine} \\ W & \mbox{output work (kJ)} & CPMS & \mbox{Comprehensive Polytropic Model of Stirling engine} \\ W & \mbox{volume (m^3)} & \mbox{kWe} & \mbox{Kilowatts of electrical power} \\ R_{cond} & \mbox{conduction resistance (m K W^{-1})} & \mbox{DDE} & \mbox{Ordinary Differential Equation} \\ R_{reck} & \\ \end{array}$ | Q | heat transfer (kJ) | r | regenerator |
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| ReReynolds number wh heater wallSstroke (m) wk cooler wallStStanton number $Abbreviation$ Ttemperature (K) or torque (Nm) $Abbreviation$ uthe velocity of gas flow (ms ⁻¹) CFD Computational Fluid Dynamicsu_p or \dot{x}_p the linear velocity of the piston (ms ⁻¹)CFDComputational Fluid DynamicsWoutput work (kJ)CPMSComprehensive Polytropic Model of Stirling engine \dot{W} power (kW)GPUGround Power UnitVvolume (m ³)kWeKilowatts of electrical power k_{cond} conduction resistance (m KW ⁻¹)ODEOrdinary Differential Equation \dot{x}_p piston acceleration (m s ⁻²)SVLPolytropic analysis of Stirling engine with Various Losses | r | crank radius (m) | 0 | environment condition |
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| StStanton numberAbbreviationTtemperature (K) or torque (N m)Abbreviationuthe velocity of gas flow $(m s^{-1})$ CFDComputational Fluid Dynamicsup or \dot{x}_p the linear velocity of the piston $(m s^{-1})$ CFDComputational Fluid DynamicsWoutput work (kJ)CPMSComprehensive Polytropic Model of Stirling engine \dot{W} power (kW)GPUGround Power UnitVvolume (m^3) kWeKilowatts of electrical power R_{cond} conduction resistance $(m K W^{-1})$ ODEOrdinary Differential Equation \ddot{x}_p piston acceleration $(m s^{-2})$ PSVLPolytropic analysis of Stirling engine with Various Losses | S | stroke (m) | wk | cooler wall |
| Ttemperature (K) or torque (N m)Abbreviationuthe velocity of gas flow $(m s^{-1})$ CFDComputational Fluid Dynamicsup or \dot{x}_p the linear velocity of the piston $(m s^{-1})$ CFDComputational Fluid DynamicsWoutput work (kJ)CPMSComprehensive Polytropic Model of Stirling engine \dot{W} power (kW)GPUGround Power UnitVvolume (m^3) kWeKilowatts of electrical power R_{cond} conduction resistance $(m K W^{-1})$ ODEOrdinary Differential Equation \ddot{x}_p piston acceleration $(m s^{-2})$ PSVLPolytropic analysis of Stirling engine with Various Losses | St | Stanton number | | |
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| \vec{W} power (kW) \vec{GPU} $\vec{Ground Power Unit}$ \vec{V} volume (m ³)kWeKilowatts of electrical power R_{cond} conduction resistance (m K W ⁻¹)ODEOrdinary Differential Equation \vec{x}_p piston acceleration (m s ⁻²)PSVLPolytropic analysis of Stirling engine with Various LossesGreek | W | output work (kJ) | CPMS | Comprehensive Polytropic Model of Stirling engine |
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| \vec{x}_p piston acceleration (m s ⁻²) PSVL Polytropic analysis of Stirling engine with Various Losses <i>Greek</i> | Raard | conduction resistance (m K W^{-1}) | ODE | Ordinary Differential Equation |
| Greek | - cona X | piston acceleration (m s ^{-2}) | PSVI. | Polytropic analysis of Stirling engine with Various Losses |
| Greek | мp | proton accoleration (mb) | | |
| | Greek | | | |
| n efficiency | n | efficiency | | |

compression processes as well as effects of non-ideal heat recovery of the regenerator, non-ideal heat transfer in cooler and heater, and pressure drops in heat exchangers. Their model was called as the Simple or Adiabatic model and later, this model was used by a number of researchers [7-12] to be modified for various loss mechanisms of real engines. In a new branch of the second-order models, the adiabatic expansion/compression processes of previous studies were substituted with polytropic processes [10-12]. In a more recent work, Babaelahi and Sayyaadi [25] developed a new thermal model called as PSVL (polytropic analysis of Stirling engine with various losses). In their

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work, the adiabatic or isothermal assumption of expansion/compression processes of previous works [15-24] was substituted with polytropic processes. In addition, the effects of the shuttle conduction heat loss, mass leakage from the working spaces to the crankcase, finite motion of the piston (based on finite speed thermodynamic model), mechanical friction, gas throttling, longitudinal conduction loss along the regenerator's wall, non-linear distribution of temperature along the regenerator, and non-isothermal behavior of the heater/cooler were considered in those generations of polytropic second-order model. In a modification on PSVL, Sayyaadi and Babaelahi [11] modified their

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