Development of a Virtual DBRE Simulation Tool

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A VIRTUAL DBRE ENGINE SIMULATION (VDBRES)

The DBRE engine concept promises significant improvements in engine performance, fuel economy and NVH over conventional reciprocating engine designs. Manipulation of its unique design parameters allows for a variety of engine geometries and performance characteristics. The relative interaction of these parameters and their subsequent optimization for a target design will be numerically assessed through development of a Virtual DBRE Simulation tool, or VDBRES. VDBRES will be developed within TECAT's custom virtual dynamometer environment to enhance the usability of the tool for subsequent prototype development. More information on TECAT's virtual dynamometer can be found via the following link: http://www.tecplot.com/showcase/studies/case_study.aspx?article=1&issue=22&pr=true

Equations of motion will be derived to produce analytical solutions of instantaneous volume and surface area of the various compression chambers. These relations will be used as the kinematic core of VDBRES to describe the motion of the ducted blades as they rotate through the circumferentially oriented working fluid chambers. Additional sub-models account for instantaneous port flows, gas-to-surface heat transfer, pre-mixed and diffusion-controlled heat release rates, mean and turbulent kinetic energy, mass, and momentum transport, and kinetic and equilibrium reaction of chemical species. These models will be modified for the VDBRES from a parent two-stroke diesel code developed by Baker. Independent control volumes for the various compression chambers will be established and connected through appropriate porting. Thermal network models will be implemented to track thermal energy distributions within components and to predict influences of external surface convection.

VDBRES will be capable of predicting system temperatures and pressures, internal and external surface temperatures, engine torque, power, heat rejection, fuel economy, thermal efficiency, cooling requirements and various other performance parameters as a function of engine speed, fueling rate, manifold conditions and key design parameters (i.e.-accumulator dimensions, ducted-blade dimensions, port locations, chamber dimensions, etc.). At the conclusion of the VDBRES development effort, an analytical investigation of key design parameters will be performed to evaluate their impact on engine performance and fuel economy. Design parameter sensitivity will be assessed over various load and speed conditions. From these results, an initial prototype design will be specified in an effort to achieve power density and fuel economy targets.

In its current version, the two-stroke Diesel Engine Simulation (DES) models each fluid chamber of the system as a quasi-steady, open system control volume containing a homogeneous ideal mixture of air and residual gas. A mass continuity and first law analysis of each component, coupled with the equation of state, form a set of non-linear differential equations which are simultaneously solved at each time step to predict the instantaneous temperature, pressure and residual fuel fraction within each system control volume. Mass flows across ports are modeled as quasi-steady, adiabatic, one dimensional, compressible flows. Experimentally measured discharge coefficients provide corrections to ideal mass flow equations. A transient heat conduction model, using a finite differencing technique, predicts heat loss from manifolds, connecting pipes, combustion chambers and annulus regions. Convective boundary conditions are determined using available engine correlations based on turbulent flow in pipes. Radiative boundary conditions, based on the adiabatic flame temperature of the burned gas are used during combustion. Mixture gas properties are calculated assuming ideal gas behavior of ten chemical species. Chemical dissociation of the combustion products is considered at temperatures exceeding 1000K below which the products are considered to be an ideal mixture of non-reacting gases.

DES treats the two-stroke diesel cycle as a sequence of continuous processes: induction, compression, combustion (including expansion), and exhaust. Induction and exhaust manifolds interact with each of the cylinders based on phase shifted cylinder solutions. Upstream/downstream turbo-component models use gearing ratios and manifold mass flow rates to estimate the initial system pressures between components. Subsequently, turbomachinery performance maps determine component mass flow rates and efficiencies, and the process repeats until mass flow rates between the components and to all manifolds converge with reciprocator mass flow rates. Turbo-compressor work is supplied by either engine shaft work or by a downstream exhaust turbine. The turbocharger speed is determined based on compressor demand and turbine power using an appropriate angular momentum relation which accounts for component inertia. These models have been validated through experimentation and previously used to successfully develop two-stroke diesel engine prototypes for military applications.

Successful development of a virtual DBRE engine will be achieved by leveraging these previously developed and validated engine simulation tools. TECAT has developed comprehensive zero, quasi, and multi-dimensional numerical simulations of 2-cycle diesel engines. The initial objective is to develop a zero-dimensional, transient system simulation for the DBRE cycle as outlined below.

TECHNICAL OBJECTIVES

Five primary objectives have been identified for the virtual engine development effort:

1.) Define a target platform for parametric analysis (i.e.- radially varying displacement vs. axially varying displacement, port geometry, transfer passage orientation, etc.)
2.) Replace appropriate sub-models within DES to simulate a DBRE. More specifically,
    - Analytically solve and implement equations describing time rate of change of volumes and surface areas of working fluid chambers
    - Analytically solve and implement equations describing the time rate of change of port openings
    - Parametrically define all working fluid chambers, ports, transfer passages,

  - Modify convective correlations based on design parameters to calculate local Reynolds velocities and to determine convective surface areas for heat transfer models,

3.) Phase-image chamber solutions to combine compression cycles into a common accumulator and phase distribute combustion product solution out to multiple expansion chambers.

4.) Use VDBRES to perform a parametric study of a target DBRE engine design. Investigate parametric sensitivity on performance and fuel economy. Parametric studies may include: # of DP's/chambers, swept volume, port size and timing, transfer passage dimensions, accumulator dimensions,

5.) With appropriate parametric selection for the initial prototype established, perform speed/load sweeps to predict performance maps for the engine – establish final DBRE engine prototype specifications for a subsequent build phase.

TECHNICAL WORK PLAN

Dr. Douglas Baker has been active in the development and use of computational models for design of internal combustion engines for over twenty years. A modular format has been developed in which system sub-models can readily be ported from existing cycle simulations to new ones. This commonalty of standard components allows for an efficient build-up of new simulation programs, facilitates cross-checking of new simulation sub-models with previously tested simulations, and permits relatively easy upgrading or modification of sub-models as simulation goals change or more accurate sub-models become available. His background and existing base of engine component models will be used to develop the system model for the DBRE.

The first four months of the scheduled Phase I numerical work effort will be dedicated to modeling and validation of primary system components, specifically, the induction, compression and mass transfer systems defined by the DP's, chambers, ports, accumulator and control valves. DES currently treats the two-stroke diesel cycle as a sequence of continuous processes: induction, compression, combustion (including expansion) and exhaust. Each process occurs within every cylinder of the engine, however, only one cylinder solution is obtained while other cylinder solutions are phased images of the first. Induction and exhaust ports interact with each of the cylinders based on phase shifted cylinder solutions. These techniques will be applied to the DBRE virtual engine simulation.

Over the next few months (months 4-6), VDBRES will be validated and calibrated using experimental results from a ducted blade pneumatic compressor prototype that has been developed in parallel by AMW. High-speed chamber pressure data will be used to estimate blow by losses and evaluate ring seal effectiveness. If necessary, blow-by loss models will be implemented into the numerical simulation to determine the impact on performance.

The final focus of the numerical phase will be on using VDBRES to perform extensive sensitivity sweeps of key design parameters and to evaluate various system components in order to optimize system packaging for a target design. Port positioning and sizing, compression ratio, DP size/sweep/transfer passage dimensions, injection timing, manifold sizing, and various other parameters will be evaluated to understand performance trends.

A prototype DBRE development effort should be started within four to six months from the start of the numerical effort and targeted for completion within six to eight months. A separate workplan and budget for the prototype DBRE development and testing phase should be developed prior to completion of the virtual engine development phase.

RELATED WORK

Dr. Baker, founder of TECAT Engineering, Inc., has worked extensively in the area of numerical engine modeling and has provided consulting services to Big Three automakers for development of global systems models for predicting thermal distributions within engines using coupled thermodynamic and thermal engine simulations. These projects included significant experimental validation which provided a high level of confidence in the numerical algorithms that were developed. He has been a co-instructor for an annual short course offered through the University of Michigan Center for Professional Development entitled *Modeling and Computer Simulation of Internal Combustion Engines.* Dr. Baker was the principal investigator of a successfully completed Phase I DOD SBIR award through the Naval Air Warfare Research Division of the DOD to develop a Separate Process Diesel gas cycle and has completed numerous Phase I/Phase II programs for development of multiple inwardly-opposed 2-stroke diesel engine platforms. He has extensive experience with evaluating alternative gas cycle concepts. His expertise in the areas of engine modeling will significantly contribute to the successful development and analysis of the DBRE gas cycle and engine design.

BUDGET REQUIREMENTS

TECAT anticipates a monthly budget requirement of 30K/month during the development phase of the virtual DBRE. The budget will primarily be used for labor & overhead of software development engineers. This development phase is expected to be complete within a six month timeframe. Costs associated with the parallel development effort for the DB compressor are not included in this budget estimate.

Subsequent DBRE prototype development, including fueling system support and controls, instrumentation, testing, and comparison with analytical data is expected to take between six to eight months after completion of the numerical investigation and has a rough order of magnitude (ROM) costs of between 500-600K. A separate workplan and detailed budget will be completed for the prototype development phase prior to completing the numerical investigation.