2015 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 4-6, 2015 - NOVI, MICHIGAN

A PASSIVE SOLUTION FOR TRANSIENT HEAT LOAD ISSUES USING PHASE CHANGE MATERIALS

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ABSTRACT

Thermal management systems (TMS) of armored ground vehicle designs are often incapable of sustained heat rejection during high tractive effort conditions and ambient conditions. The use of a latent heat energy storage system that utilizes Phase Change Materials (PCMs) is an effective way of storing thermal energy and offers key advantages such as high-energy storage density, high heat of fusion values, and greater stability in temperature control. Military vehicles frequently undergo high-transient thermal loads and often do not provide adequate cooling for powertrain subsystems. This work outlines an approach to temporarily store excess heat generated by the transmission during high tractive effort situations through use of a passive PCM retrofit thereby extending the operating time, reducing temperature transients, and limiting overheating. A numerical heat transfer model has been developed based around a conceptual vehicle transmission TMS. The model predicts the transmission fluid temperature response with and without a PCM retrofit. The developed model captures the physics of the phase change processes to predict the transient heat absorption and rejection processes. The model will be used to evaluate the effectiveness of proposed candidate implementations and provide input for TMS evaluations. Parametric studies of the heat transfer model have been conducted to establish desirable structural morphologies and PCM thermophysical properties. Key parameters include surface structural characteristics, conduction enhancing material, surface area, and PCM properties such as melt temperature, heat of fusion, thermal conductivity, etc. To demonstrate proof-of-concept, a passive PCM enclosure has been designed to be integrated between a transmission bell housing and torque converter. This PCM-augmented module will temporarily strategically absorb and release heat from the system at a controlled rate. This allows surging fluid temperatures to be clamped below the maximum effective fluid temperature rating thereby increasing component life, reliability, and performance. This work outlines cooling system boundary conditions, mobility/thermal loads, model details, enclosure design characteristics, potential PCM candidates, design considerations, performance data, cooling system impacts, conclusions, and potential future work.

INTRODUCTION

Today's tactical wheeled vehicle and combat vehicle fleets are frequently operated under high-tractive effort conditions. The majority of these vehicles do not offer the ability to absorb and eliminate the heat created when operating under these conditions. One particular area of concern is the Thermal Management Systems' (TMS) inability to cool the transmission fluid under ultra-high load transient conditions. Some of these conditions are seen when towing a like vehicle, towing a trailer, a combat vehicle places all of its weight on one track, operating in soft soils, climbing a grade or step, operating at slow speeds with large electrical power draws, or when mired in frozen mud or ice. During these conditions transmission fluid temperatures rise rapidly, which often leads to fluid overheating. When this happens, there is a high likelihood for premature failure of the transmission or torque converter. Each year 14 million transmissions fail. Of these, nine out of ten failures are attributed to overheating [1]. Rather than increasing the capacity of the main cooling stack transmission heat exchanger, which would impose additional burden to the overall TMS and considerable system redesign, a more passive approach could be utilized to control the transient heat loads. The passive approach could be accomplished through use of an encapsulated PCM matrix around the torque converter packaged in the bell-housing between the engine and transmission. This approach is discussed in detail throughout this paper.

STRATEGIC RESEARCH PLAN

The aim of this research is to develop a low-cost passive approach to resolve the transient transmission cooling issues that are regular occurrences on tactical wheeled and combat vehicles by use of an encapsulated PCM matrix. In order to provide proof-of-concept that the proposed method is capable of clamping the rapidly rising fluid temperatures a strategic research plan was implemented. This plan consists of the following: identify a target vehicle platform and associated cooling system, characterize the vehicles cooling system by use of modeling and simulation and full load cooling vehicle testing, utilize CAD to design an actual PCM matrix enclosure, analyze cooling performance data to identify the heat load generated under 0.6 Tractive Effort (TE) to weight ratio conditions, survey commercially available PCMs, identify optimal Conduction Enhancing Material (CEM), identify system boundary conditions, generate core equations and methodology for the numerical heat transfer model, build numerical heat transfer model using LabView, optimize the model to include all critical independent variables, utilize the model to identify baseline performance, perform iterative model simulations to develop the optimal system design, and finally utilize the model to provide proof of concept that the PCM matrix enclosure does extend operating time under high TE conditions.

ENCLOSURE DESIGN

The design of the enclosure is critical to overall performance as optimizing design allows for the maximum surface contact area and PCM matrix depth. CAD modeling considering a SAE#2 bell-housing and Allison transmission was used to generate the enclosure design. This modeling generated the actual face area ($A_{PCM} = 0.16 m^2$) and PCM matrix depth values that were used in the analysis. A visual representation of the PCM matrix enclosure is shown in Figure 1.

Figure 1. PCM Matrix Enclosure

The enclosure was designed to mechanically mount to the six torque converter bosses and the engine flywheel. The enclosure will therefore absorb heat directly from the torque converter housing. The internal structure is designed to ensure robustness in the PCM matrix enclosure and overall drivetrain.

PCM AND CEM SELECTION

Selection of a candidate PCM is a critical part of the system design. The PCM has to meet criteria set forth by the surrounding system. The PCM melting temperature needs to be less than the maximum allowable transmission fluid temperature and above the nominal operating temperature to ensure the PCM serves as a reserve capacity for high tractive effort operations. To maximize absorption in a compact space, it is imperative that a material with a high heat of fusion value is chosen. A survey of numerous PCMs was conducted and magnesium chloride hexahydrate ($MgCl_2$-$6H_2O$) was chosen as the baseline candidate. $MgCl_2$-$6H_2O$ has a melting temperature of 117ºC, which is higher than the nominal transmission temperature under steady state operations but lower than the maximum transmission return temperature limit. It also has a very high heat of fusion value, 167kJ/kg [2]. Other factors such as environmental, weight, availability, and cost make MgCl2-6H2O an ideal candidate as a PCM for this analysis. Unfortunately, PCM materials, in general, have limited thermal conductivity in both solid and liquid phases. In an effort to increase the rate at which the enclosure pulls heat out of the system and heat is transferred into the PCM matrix, a Conduction Enhancing Material (CEM) is needed. The CEM chosen for this study is a porous aluminum matrix. The interstitial spaces within the porous matrix are impregnated with the PCM. The aluminum structure provides thermal conductivity enhancement to promote heat penetration into the matrix.

MODEL FORMULATION

In an effort to demonstrate the feasibility of implementing a PCM matrix retrofit to increase high TE operation time, a numerical model was developed. The thermal response of typical transmission cooling systems is often dependent upon platform-specific designs and can demonstrate considerable intersystem dependency. For the purposes of this study, a simplified, representative transmission cooling system was developed to illustrate the effects of a PCM matrix retrofit. Consider the fluid loop representation of the transmission cooling system shown in Figure 2. The transmission fluid is assumed to flow to an air-cooled heat exchanger for rejection of system waste heat.

The fluid thermal response of the simplified cooling loop can be written as:

$$C_f \frac{dT_b}{dt} = \dot{Q}_{tx} - \dot{Q}_{tb} - \dot{Q}_{hx} - \dot{Q}_{PCM} \quad (1)$$

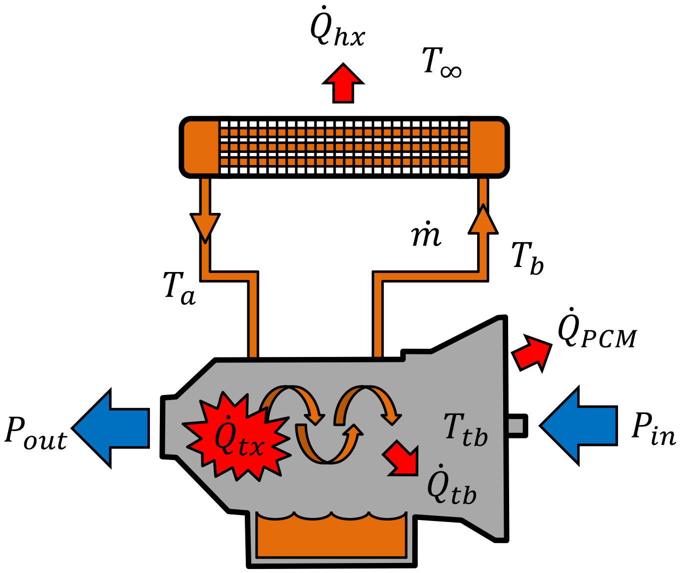


Figure 2. Simplified Transmission Cooling System

This expression states that the fluid thermal inertia ($C_f \frac{dT_b}{dt}$) is equal to the fluid heat generation ($\dot{Q}_{tx}$) minus the heat absorbed by the transmission body ($\dot{Q}_{tb}$), minus the heat exchanger rejection rate ($\dot{Q}_{hx}$), minus the heat absorbed by the PCM ($\dot{Q}_{PCM}$). The fluid heat generation term represents the waste heat generation rate imposed by power transmission inefficiencies. The heat absorption by the transmission body represents a thermal inertia of the transmission and associated system and links the fluid temperature to an effective transmission body temperature. The heat rejection rate ties the heat exchanger performance to the fluid and ambient temperatures. The PCM heat absorption term represents the rate of energy absorption and ultimate rejection of thermal energy to/from the PCM matrix.

Actual vehicle design data for the standard vehicle transmission cooling system was utilized and inputted into the model to identify baseline performance levels. One of the key parameters in the model is the actual heat load created when the vehicle is under a 0.6TE/WT condition. Since the accuracy of this value is so critical special consideration was given to ensure this value was consistent with heat loads present during actual high TE conditions. To characterize the heat load a combination of Allison SCAAN (System for Computerized Application Analysis) modeling data and Full Load Cooling (FLC) testing done at the Yuma Proving Grounds (YPG) was utilized. The test data and system modeling yielded an estimated heat load of 19.95kW during high TE conditions. Once the accurate data was obtained the model was able to generate performance levels for this standard system. The transient response of the transmission cooling system from steady-state operations prior to high TE operations is shown in Figure 3. This behavior is representative of actual vehicle transmission cooling system response and serves as the baseline for comparison to the concept PCM response.

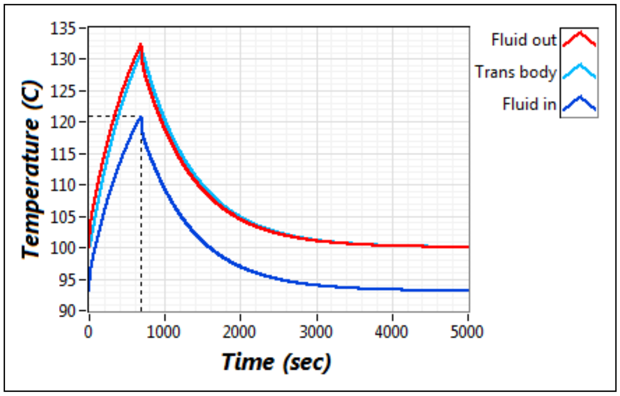


Figure 3. Baseline Cooling System Performance under High TE Condition

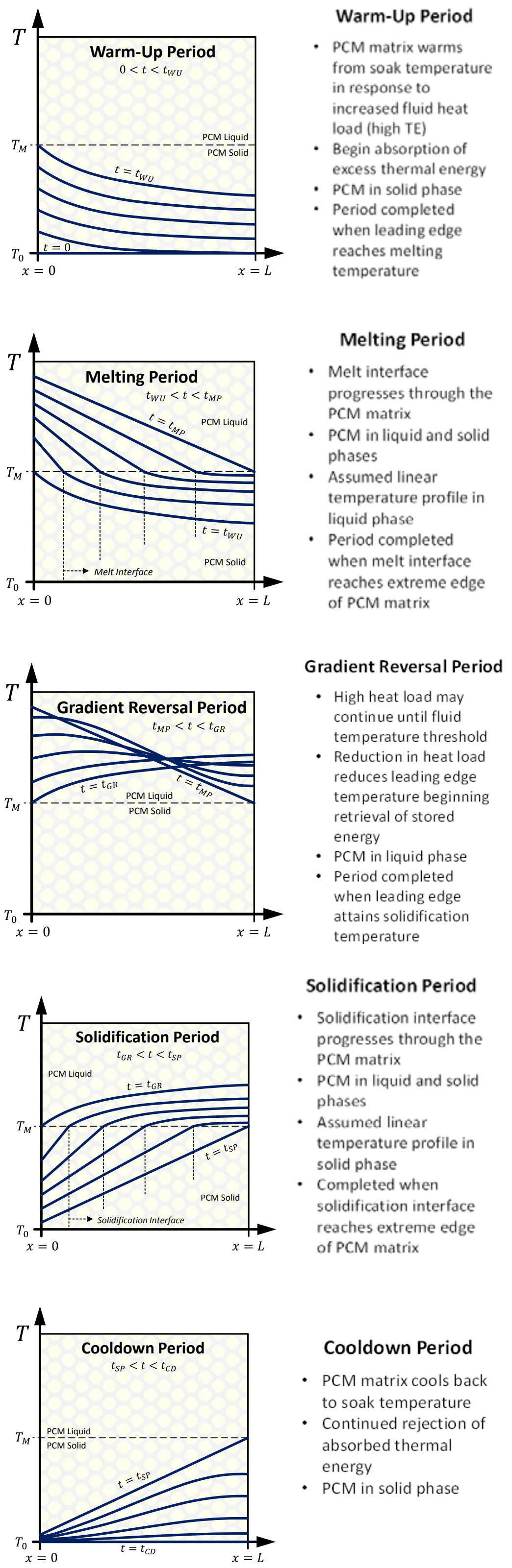
The PCM matrix is a two-component assembly composed of a porous metal matrix impregnated with the phase change material. For this study, the PCM matrix has been assumed to retrofit into the existing bell housing volume and is coupled directly to the transmission torque converter. High fluid velocities, turnover and mixing of the fluid volume within the torque converter, promotes the use of a one-dimensional solution to the heat transfer mechanisms within the PCM matrix. This assumption implies that the fluid temperature within torque converter has no temperature variation tangential to the PCM matrix interface and the processes of the PCM matrix thermal absorption and rejection are normal to the interface.

There are five distinct time periods that can be identified over the duration of the PCM matrix thermal absorption and rejection. Each of these time periods have a unique set of governing relations, boundary, and initial conditions. In general, the solution methodology utilizes the method eigenfunction expansion with additional provisions for melt front propagation. The five time periods have been identified as:

- Warm-Up Period
- Melting Period
- Gradient Reversal Period
- Solidification Period
- Cooldown Period

In the model, these five time periods execute sequentially to predict the transient response to an imposed steady-state heat load under high TE conditions. The general behavior of expected temperature profiles during each of these time periods are shown in Figure 4. The Warm-Up Period constitutes absorption of sensible heat as the PCM matrix warms from a pre-high TE condition to the onset of melting. The Melting Period encompasses the melting processes as the melt layer progresses through the PCM matrix. The Gradient Reversal Period includes the reduction in heat load and subsequent cooling of the matrix back to the point where the solidification process begins. The Solidification Period is the progression of the solidification front through the matrix and the Cooldown Period covers the settling of the temperature profiles back to pre-high TE conditions.

For each of the time periods in the PCM solution, the underlying models are based upon solution of the transient heat equation (first order in time, second order in space) in the PCM matrix coupled to a first order in time differential equation for the system-level response. Where appropriate, the method of eigenfunction expansion was utilized to reduce the heat equation to a set of first order ordinary differential equations in time. During the phase change periods of melting and solidification an additional constituent relationship was developed, based on a phase change front energy balance to establish a first order differential for the location of the melt/interface location. The coupled set of differential equations derived for each time period were solved using a 4th-order Runge-Kutta solution methodology.



Warm-Up Period

- PCM matrix warms from soak temperature in response to increased fluid heat load (high TE)
- Begin absorption of excess thermal energy
- PCM in solid phase
- Period completed when leading edge reaches melting temperature

Melting Period

- Melt interface progresses through the PCM matrix
- PCM in liquid and solid phases
- Assumed linear temperature profile in liquid phase
- Period completed when melt interface reaches extreme edge of PCM matrix

Gradient Reversal Period

- High heat load may continue until fluid temperature threshold
- Reduction in heat load reduces leading edge temperature beginning retrieval of stored energy
- PCM in liquid phase
- Period completed when leading edge attains solidification temperature

Solidification Period

- Solidification interface progresses through the PCM matrix
- PCM in liquid and solid phases
- Assumed linear temperature profile in solid phase
- Completed when solidification interface reaches extreme edge of PCM matrix

Cooldown Period

- PCM matrix cools back to soak temperature
- Continued rejection of absorbed thermal energy
- PCM in solid phase

Figure 4. Time Periods and Expected Temperature Profiles of the PCM matrix Thermal Absorption and Rejection Processes

MODEL OPTIMIZATION

The model currently has 26 independent parameters in the simulation encompassing boundary conditions, system properties, morphology parameters, and material properties. Several optimization studies have been conducted to identify the optimal values for certain key parameters such as CEM porosity and PCM matrix depth. The plot in Figure 5 represents maximum PCM depth layer as a function of porosity and PCM surface area. PCM matrix depth is the melt layer penetration at the limit of transmission fluid return temperature. Greater surface means more heat removal from the coolant allowing greater penetration depth and therefore even more heat removal. As the porosity of the CEM increases, heat absorption becomes limited by conduction. As the porosity decreases, the CEM thermal conductivity contributes further, increasing the melt penetration.

The plot in Figure 6 displays the additional high TE operating time afforded by the use of PCM matrix retrofit. Although lower porosities allow greater penetration depth as demonstrated in Figure 5, lower porosities also imply less PCM contributing to energy absorption. This results in a decrease in increased operating times at lower porosities. As the porosity increases, conduction limitations into the PCM matrix reduce the quantity of PCM participation. These effects are clearly observed in Figure 6 and demonstrate that an optimal CEM porosity is approximately 0.4 and is relatively independent of the PCM contact area.

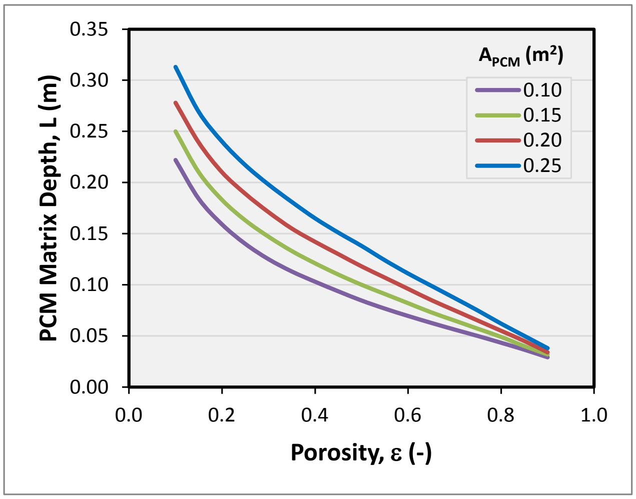


Figure 5. PCM depth layer as a function of porosity and PCM surface area

Note that these results are dependent upon the specific selection of system parameters and material properties. The PCM matrix retrofit would need to be tailored to a specific design to optimize performance.

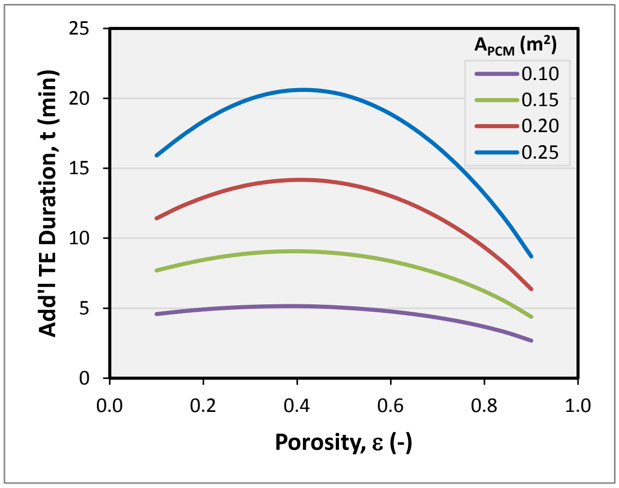


Figure 6. Additional high TE time as a function of porosity and PCM contact area.

MODEL ANALYSIS

The analysis of additional operational time performed above illustrate the effects of CEM porosity and PCM matrix contact area. However, system response times are also dependent upon ambient temperature as shown in Figure 7. As the ambient temperature decreases, the thermal management system has a greater ability to reject waste heat. Figure 7 illustrates the high TE operational time for the baseline system design and the operational time for a PCM matrix augmented system with maximum PCM melt layer penetration depth. As the ambient temperature decreases and the system heat exchanger can reject more heat, the melt layer depth grows substantially. However, packaging considerations will limit the allowable thickness of a PCM matrix retrofit.

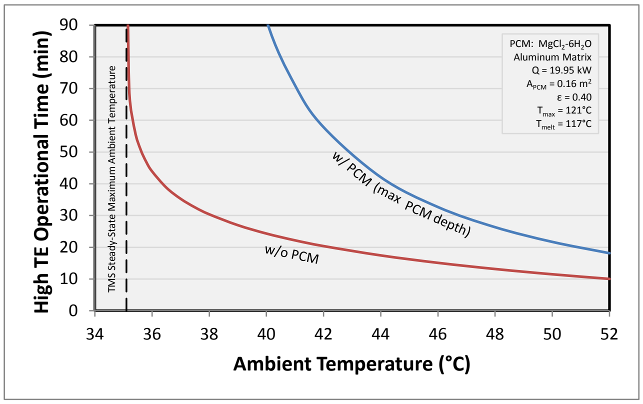


Figure 7. Additional high TE time as a function of ambient temperature.

To illustrate the expected behavior of a particular installation, the additional high TE operational time is shown as a function of ambient temperature and PCM matrix thickness in Figure 8 displays the predicted difference in additional high TE operation time for several PCM matrix thicknesses.

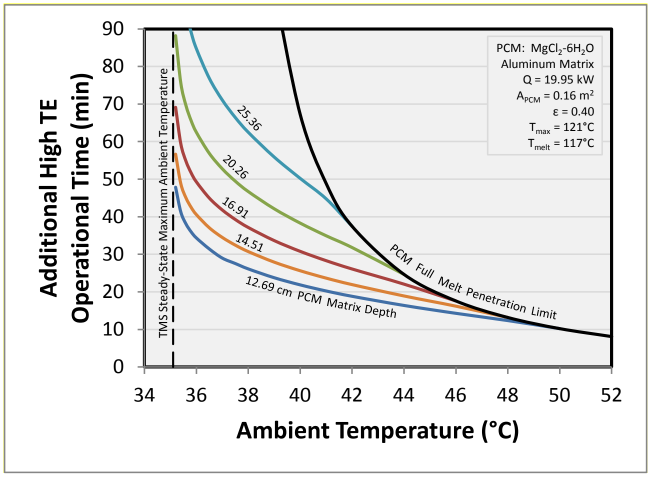


Figure 8. Additional high TE time for several PCM matrix depths

Consider the 12.69 cm PCM matrix depth solution shown in Figure 8. Under these operating conditions, this application would yield an additional ten minutes of high TE operations at an ambient temperature of 50°C. If the ambient temperature is reduced to 37°C, the additional operational time is increased to approximately 30 minutes. If an even greater increase is desired, the vehicle integrator must consider a larger PCM matrix depth or an externally mounted PCM thermal absorber.

MODEL RESULTS

Comparative results between the transient system performance with and without the PCM matrix are shown in Figures 3 and 9. The model calculates the duration of high TE (high heat load) that system can support before the fluid temperature reaches the temperature threshold. Figure 3 illustrates the transient temperature response of the baseline cooling system. Figure 9 shows the response of the system with the PCM Matrix retrofit under the same operating conditions. The standard vehicle transmission cooling system would be able to operate for 690.2 seconds before the maximum transmission return temperature is reached. Figure 9 shows that with the PCM retrofit, the high TE operating time is extended to 1302.7 seconds. This represents an increase of 612.5 seconds (10.2 minutes) of high TE operating time. Figure 9 also displays where the five outlined periods take place.

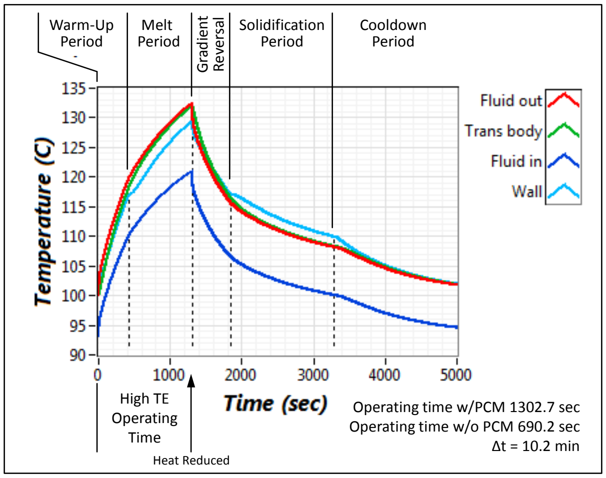


Figure 9. Overal baseline sytem performance vs PCM system performance

FUTURE WORK

Future studies will include the development of a more comprehensive model of particular installation and the fabrication of a prototype PCM matrix enclosure. Platform-specific details may have considerable affect on the optimal design parameters and a targeted vehicle installation should be investigated for further study. Once a platform-specific analysis is completed to include integration design considerations, the fabrication of a prototype PCM matrix enclosure can be used with an Allison transmission to simulate the proposed design evaluated in this study. A benchscale prototype experiment with controlled fluid temperatures could be developed to simulate high tractive effort conditions and compare to existing vehicle test data. If the benchscale testing continues to show promise, a full transmission dynamometer demonstration would be warranted.

SUMMARY & DISCUSSION

The results of this study illustrate that incorporating a PCM matrix enclosure within the transmission bellhousing does provide a practical method to passively increase high TE operation time without significant system redesign. In most cases this additional operational time should provide margin to overcome the high TE conditions. This additional operating time provides margin to decrease the likelihood of transmission overheating, reducing thermal failure rates, and significantly increasing transmission operational lifetime.

NOMENCLATURE

PCM	Phase Change Material
HEX	Heat Exchanger
TMS	Thermal Management System
CEM	Conduction Enhancing Material
CAD	Computer Aided Design
TE	Tractive Effort
YPG	Yuma Proving Grounds
SCAAN	System for Computerized Application Analysis

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