

REDUCED-ORDER THERMAL DIGITAL TWIN FOR PREDICTIVE MONITORING OF WEAPON SYSTEMS

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Abstract: *This study proposes a reduced-order thermal digital twin framework for predictive monitoring of weapon systems subjected to transient firing conditions. The proposed approach employs a one-dimensional transient heat conduction model formulated in cylindrical coordinates which is experimentally validated through successive firing test performed on a small-caliber weapon system, using external barrel temperature measurements acquired during firing scenarios. The obtained results demonstrate that the reduced-order formulation successfully reproduces the thermal behavior associated with barrel heating and cooling processes while maintaining significantly lower computational requirements compared to high-fidelity numerical simulations. Furthermore, the proposed framework enables near real-time thermal estimation capabilities suitable for predictive monitoring, thermal safety assessment, and future smart defense applications. The computational efficiency and physical consistency of the model also support its potential integration into digital twin architectures and dual-use thermal monitoring systems.*

Keywords: heat transfer, predictive monitoring, smart defense systems, reduced-order modeling

1. Introduction

The thermal behaviour of weapon systems subjected to repetitive firing conditions represents a critical factor influencing operational safety, structural integrity, firing accuracy and service life. During firing sequences, the barrel is exposed to severe transient thermal loads generated by high-temperature propellant gases, producing significant thermal gradients and accelerating degradation phenomena such as thermal fatigue, erosion, and wear [1, 2]. Excessive thermal accumulation may also increase the probability of cook-off events and reduce operational reliability. Consequently, accurate thermal prediction and monitoring have become increasingly important for modern smart defense systems and predictive maintenance strategies. Recent advances in computational

engineering enabled the development of high-fidelity CFD and FEM models capable of accurately reproducing transient thermal phenomena in weapon barrels [3, 4]. Although these approaches provide detailed thermal field distributions, their elevated computational cost limits their applicability in near real-time monitoring environments and embedded diagnostic systems [3]. To address these limitations, several researchers investigated reduced-order thermal approaches based on one-dimensional transient heat transfer formulations [1, 5, 6]. Such models provide computational efficiency and numerical stability while maintaining acceptable predictive capability for engineering applications involving repetitive firing conditions. In parallel, digital twin (DT) technologies have emerged as promising tools for

predictive monitoring and intelligent maintenance of complex engineering systems. Reduced-order models are particularly suitable for DT implementations because they enable near real-time thermal estimation while preserving physical consistency [7]. However, despite the growing interest in predictive monitoring architectures and digital twin technologies in thermal engineering applications, current research dedicated to weapon systems remains primarily focused on offline thermal analysis and high-fidelity numerical simulations, while limited attention has been directed toward reduced-order thermal digital twin frameworks suitable for near real-time monitoring.

Therefore, the present study proposes a reduced-order physics-based thermal digital twin framework for predictive monitoring of weapon systems operating under transient firing conditions. A one-dimensional transient heat transfer model is implemented using a finite difference numerical approach and experimentally validated under successive firing scenarios. The proposed framework aims to provide computationally efficient thermal prediction capabilities suitable for future predictive safety assessment and smart defense applications.

2. State of the art in thermal monitoring of weapon systems

2.1. Analytical and reduced-order thermal models

Reduced-order thermal models have been widely employed for transient thermal analysis of weapon barrels due to their computational efficiency and implementation simplicity [5, 6]. One-dimensional heat transfer formulations are particularly attractive for rapid thermal estimation under repetitive firing conditions, enabling efficient prediction of barrel temperature evolution with relatively low computational cost [3]. Finite difference method (FDM) implementations remain among the most commonly used numerical approaches because of their numerical

stability and suitability for repeated simulations.

Several studies demonstrated that reduced-order thermal models can provide acceptable agreement with experimental measurements while significantly reducing computational effort compared to high-fidelity simulations [3]. Nevertheless, most existing reduced-order approaches are primarily focused on offline thermal analysis rather than predictive monitoring or digital twin integration.

2.2. CFD and high-fidelity thermal models

CFD and FEM approaches are extensively used for detailed investigation of transient thermal behaviour, thermo-mechanical coupling, and heat transfer phenomena in weapon systems [3, 8]. These methods enable accurate characterization of thermal gradients, stress accumulation, and localized overheating effects occurring during firing sequences.

Despite their high predictive capability, high-fidelity numerical models generally require extensive computational resources, fine spatial discretization, and long simulation times. Consequently, their direct implementation in near real-time monitoring architectures or embedded predictive systems remains challenging. Recent research trends increasingly investigate hybrid multifidelity approaches combining detailed high-fidelity simulations with computationally efficient reduced-order models to support predictive and real-time capable digital twin applications [9].

2.3. Digital twin and predictive monitoring approaches

Digital twin technologies are increasingly employed in aerospace, manufacturing, and energy systems for predictive maintenance and operational optimization [7, 9]. In the field of artillery equipment protection, Wu et al. emphasize that digital twin technology may overcome the limitations of regular maintenance and after-the-fact repair by supporting more accurate condition assessment and equipment protection [10]. In joint warfighting applications, digital

twins are also described as systems that link past data and present processes while enabling future predictions based on sensor data and actionable information [11]. Recent defence-oriented research further highlights that digital twins can support real-time monitoring, proactive maintenance, logistics optimization, and predictive evaluation of military equipment and infrastructure [12]. In thermal engineering applications, reduced-order physics-based models play a critical role in enabling near real-time prediction capabilities while maintaining acceptable physical accuracy [13]. Although digital twin frameworks have been extensively investigated in industrial applications, their implementation in thermal monitoring of weapon systems remains relatively limited. Most current studies focus on offline numerical analysis rather than predictive operational monitoring or embedded thermal diagnostics. Consequently, reduced-order thermal digital twins represent a promising direction for future smart defense systems, particularly for predictive safety assessment and intelligent maintenance applications.

3. Reduced-order thermal model

To enable near real-time predictive monitoring, the digital twin architecture requires a thermal model that avoids the computational bottlenecks of full 3D simulations while preserving physical accuracy. This is achieved through a reduced-order modeling approach focused on the primary heat transfer mechanisms.

The formulation of the reduced-order model is based on the geometric and operational characteristics of standard weapon systems. The core physical assumptions are [3]:

- i. the axial heat fluxes is considered negligible compared to the radial heat transfer.
- ii. the barrel is treated as an isotropic medium. However, to maintain high fidelity under rapid-fire conditions, its thermophysical properties (thermal conductivity and specific heat) can be

dynamically updated based on the local temperature state.

- iii. reducing the spatial domain to a single dimension (1D), the model achieves the computational speed required for embedded predictive systems without sacrificing the accuracy of the thermal profile prediction.

Based on the aforementioned assumptions, the transient heat conduction through the barrel wall is governed by the one-dimensional Fourier equation in cylindrical coordinates:

$$\frac{\partial T(r,t)}{\partial t} = \frac{k}{c_p \rho_{pc}} \left[\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r,t)}{\partial r} \right] \quad (1)$$

where ρ_{pc} is the material density, c_p is the specific heat capacity, k is the thermal conductivity, and $T(r,t)$ represents the temperature field at radial position r and time t . For integration into the digital twin framework, this partial differential equation (PDE) is discretized using an explicit finite difference method (FDM), which guarantees rapid execution times suitable for live monitoring algorithms.

The predictive accuracy of the model relies entirely on the dynamic boundary conditions that couple the structural thermal response with the ballistic environment and the ambient surroundings. Therefore, the internal boundary condition is expressed as:

$$h_g(T_g - T_{(r_{int},t)}) = -k \frac{\partial T}{\partial r} \Big|_{r=r_{int}} \quad (2)$$

Here, the transient gas temperature T_g and the convective heat transfer coefficient h_g act as the forcing functions, directly imported from the internal ballistics module. At the external surface $r = r_{ext}$, the model accounts for the cooling effect via natural convection to the ambient environment:

$$h_a(T_{amb} - T_{(r_{ext},t)}) = -k \frac{\partial T}{\partial r} \Big|_{r=r_{ext}} \quad (3)$$

where T_{amb} denotes the ambient temperature and h_a represents the external convective heat transfer coefficient.

This formulation ensures that the digital twin correctly captures both the rapid heat accumulation during firing and the gradual heat dissipation during cooling phases.

The governing transient heat conduction equation is discretized using an explicit finite difference method (FDM) formulation in the radial direction. The computational domain is divided into a finite number of radial nodes extending from the inner bore radius to the external barrel surface.

Temporal integration is performed using a fixed time-stepping scheme selected according to numerical stability requirements [3]. The explicit implementation provides low computational complexity and enables rapid thermal prediction suitable for repetitive simulations and near real-time monitoring applications. The numerical algorithm was implemented in MATLAB.

The reduced-order formulation significantly decreases computational time compared to CFD or FEM simulations while preserving the capability to estimate transient barrel temperature evolution under successive firing conditions. This computational efficiency makes the proposed approach suitable for future integration into predictive monitoring architectures and thermal digital twin frameworks dedicated to smart weapon systems.

4. Experimental validation and predictive monitoring framework

To evaluate the predictive capability of the proposed reduced-order thermal model, experimental investigations were conducted under successive firing conditions using a small-caliber weapon system. The experimental test aimed to measure the transient evolution of the external barrel surface temperature during repetitive firing sequences and to compare the recorded thermal response with the numerical predictions obtained using the proposed model.

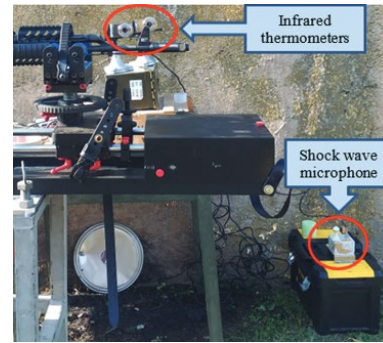


Figure 1. Experimental configuration – the assault rifle, the infrared thermometers and the shock wave microphone [3]

Temperature measurements were performed using thermocouple sensors positioned on the external barrel surface in regions characterized by significant thermal loading during firing. The sensor placement strategy was selected to ensure accurate monitoring of the transient thermal evolution. Ambient temperature conditions were recorded throughout the experimental test to ensure consistency between numerical and experimental boundary conditions.

The firing scenarios consisted of controlled successive shot sequences designed to reproduce representative operational thermal loading conditions. During each shot, the transient barrel temperature evolution was recorded for subsequent comparison with numerical predictions.

The numerical predictions obtained using the reduced-order thermal model showed good agreement with the experimentally measured barrel surface temperatures. The model successfully reproduced the transient temperature increase occurring during repetitive firing conditions as well as the subsequent cooling phase after firing interruption. The results of the theoretical model regarding the temperature variation over time were evaluated at the locations corresponding to the two temperature probes used in the experimental test.

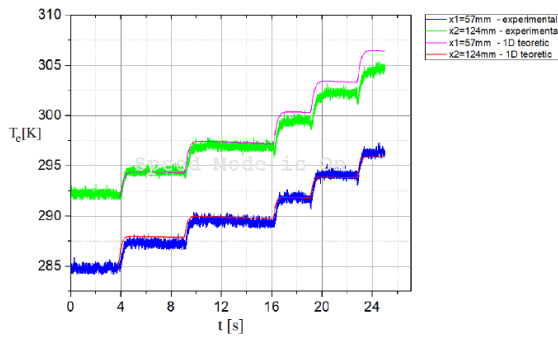


Figure 2. 1-D model simulation temperature, single shot scenario

The comparison between numerical and experimental results demonstrated that the one-dimensional reduced-order formulation captures the dominant thermal behavior governing barrel heating and cooling processes. Minor deviations observed between numerical and experimental data may be attributed to the estimation of convective heat transfer coefficients, local thermal nonuniformities, and simplified modeling assumptions [3].

4.1. Predictive monitoring perspective

The computational efficiency of the proposed model enables its potential integration into predictive thermal monitoring architectures and future thermal digital twin frameworks. Unlike computationally intensive CFD or FEM simulations, the proposed approach allows rapid thermal estimation suitable for near real-time implementation.

From a predictive maintenance perspective, continuous estimation of barrel thermal behaviour may support overheating prevention, thermal fatigue assessment, and operational safety monitoring. In addition, the proposed framework may facilitate the implementation of thermal health indicators capable of supporting intelligent maintenance scheduling and operational risk reduction strategies.

The reduced computational demand associated with the present formulation also makes it suitable for future integration into onboard monitoring systems and smart defense platforms. Furthermore, the

proposed methodology presents potential dual-use applicability in other engineering domains involving transient thermal loading conditions

Overall, the obtained results demonstrate that reduced-order thermal models can provide an effective compromise between numerical accuracy and computational efficiency, representing a promising solution for future predictive thermal monitoring applications in advanced defense systems.

5. Conclusions

The present study investigated the applicability of a reduced-order thermal model for predictive monitoring of weapon systems operating under transient firing conditions. A one-dimensional transient heat transfer formulation was implemented using a finite difference numerical approach and experimentally validated through successive firing scenarios.

The obtained results demonstrated that the proposed model is capable of reproducing the dominant thermal behavior associated with barrel heating and cooling processes while maintaining significantly lower computational requirements.

From a computational perspective, the proposed methodology offers important advantages for predictive monitoring architectures due to its numerical stability, reduced implementation complexity, and near real-time capability. These characteristics make the model particularly suitable for future integration into thermal digital twin frameworks, onboard diagnostics systems, and predictive maintenance platforms dedicated to smart defense applications.

Future research directions will focus on the integration of adaptive convective boundary conditions, sensor-assisted model updating strategies, and hybrid reduced-order Digital Twin architectures capable of supporting advanced predictive thermal diagnostics for next-generation autonomous defense systems.

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