Development of a Computer Program for Thermal Analysis of Aircraft Cooling Liners

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A user-friendly heat transfer/thermal modeling code, LinerThermTM, has been developed for rapid analysis of aircraft exhaust liner cooling systems. Most of the thermal modeling codes on the market today fall into one of two categories – either they are complex 3-D codes requiring significant engineering resources or they are simple conduction models that lack advanced convection capabilities required for high performance aerospace and propulsion cooling applications. In the high-tech field of aerospace propulsion, it is necessary that rapid modeling of complex thermal systems be accomplished to enable the trade studies required to optimize aircraft cooling liner designs for weight, cost, and performance. This code performs detailed thermal analysis of gas turbine exhaust liners used in the augmentor and nozzle and includes cooling capabilities for impingement, multi-hole film-cooled, slot filmcooled, and convectively cooled liners. Its simple user interface provides the capability of performing quick trade studies for a vast array of cooling liner designs, including a wide selection of included materials.

Nomenclature

Α	=Area	V	=Velocity
BFM	=Backflow margin	x	=Distance
C_p	=Specific heat at constant pressure	α	=Absorptivity
f/a	=Fuel/air ratio	3	=Emissivity
h	=Convective heat transfer coefficient	η	=Film effectiveness
Κ	=Luminosity factor (1.42 for JP fuel systems)	ρ	=Density
k	=Thermal conductivity	σ	=Stefan-Boltzmann constant
L	=Length	'n	=Mass flow rate
М	=Blowing ratio		-mass from rare
Р	=Pressure	Subscript	s
Pr	=Prandtl number	S	– Static
Q	=Heat load	Б Т	- Total
q	=Heat flux	aw	– Adiabatic wall
S	=Slot width	aw f	- Film-adjusted adjabatic wall
Т	=Temperature	u vv ,1	- i nin adjusted adiabatic wan

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I. Introduction

There is a continual drive to improve performance of aircraft and air vehicle systems. These improvements generally result in increased temperatures and a need for reduced weight. Turbine temperatures tend to limit the performance that may be achieved with gas turbine propulsion systems. Advanced turbine designs, including high temperature materials and cooling technologies, are required to provide further improvements in gas turbine performance. Military aircraft, such as the F-22 (Fig. 1), offer additional cooling challenges. Typical afterburning military propulsion systems in use today deliver hot gas at total temperatures near 4000°R. The exhaust nozzle must survive in this environment, while at the same time function to control engine backpressure. Future military aircraft continually seek to add features to the exhaust nozzle, such as expansion ratio control for optimum performance and vectoring control for improved maneuverability, adding to the challenge of cooling the nozzle surfaces. Propulsion system exhaust systems, including the augmentor and nozzle, generally employ cooling liners to provide adequate cooling from the 4000°R exhaust. Figure 2 illustrates a typical impingement/film cooled liner cross section. It is obvious from this figure that film cooling presents a very complex cooling system requiring advanced tools for performing the necessary thermal analysis. 3-D solvers exist but require significant engineering resources to use. In the early, conceptual stages of the design process, trade studies are usually performed to identify the technical risks and define the optimum approach to solving them. It is during this phase of the design that a simple, easy-to-use thermal tool is required to enable the analysis of many configurations, leading to the selection of the optimal approach. This is especially critical in aerospace applications where failure to achieve the best approach early in the program may result in significant costs later.



Figure 1. Lockheed F-22 "Raptor"

Film Flow Gas Path Flow Figure 2. Typical Impingement/Film Cooled Liner Cross-Section

Supply Ch

II. Technical Discussion

Since a primary characteristic of LinerThermTM is its ease of use, user-friendliness was designed into the code from its inception. This, combined with the thermal approach used within the code, has made this an easy-to-use, accurate tool for determining thermal loads and liner design requirements. Wherever possible, user input requirements have been kept to a minimum. Through selection of user-defined options, the user may select to analyze either an axisymmetric or two-dimensional (2D) nozzle. In addition, the user may also select from a library of materials whose properties have been built into the code, simplifying the user inputs.

LinerThermTM calculates exhaust system cooling flows and liner temperatures without forcing the user to create a cumbersome flow model. One of two approaches is used to calculate cooling flows and surface temperatures:

• The user specifies a constant backflow margin to be applied to all film rows throughout the exhaust system

• The backflow margin is iterated for each liner until the maximum allowable surface temperature is reached The backflow margin is defined as follows:

$$BFM = \frac{P_{s,supply}}{P_{s,gas}} - 1 \tag{1}$$

LinerThermTM is capable of analyzing various cooling schemes, including backside convection, impingement, hot side convection, multi-hole film/effusion cooling, and slot cooling. Material selection is enabled through simple drop-down menus of materials for each component. Material properties, including max use temperature and thermal conductivity, are automatically defined by the material selection. However, these properties may be over-ridden when desired. A variety of liner materials are included as defaults in LinerThermTM, with the option to select user-defined materials and properties. Thermal barrier coating is included as an option. The user may also select cost- and weight-per unit area for each liner, although these are not necessary for the code to run. Film effectiveness may be selected from a drop-down menu of published correlations, or new correlations may be input by the user through use of simple table reads.

LinerThermTM uses a 1D heat conduction model (2D for effusion) to calculate surface temperatures along each liner. Radiation is included in the calculation procedure by iterating on an effective reference temperature until convergence is reached.

A. Aerodynamic Boundary Conditions

A simple, one-dimensional (1D) approach has been used to calculate the aerodynamic boundary conditions that are needed for a thermal analysis. The required user inputs are listed (refer to Fig. 3):

- Nozzle type (axisymmetric or 2D)
- Lengths of each component (screech liner, AB liner, convergent and divergent flaps, etc.)
- Cross-sectional areas at stations 7, 8, and 9 (and 7.5 for 2D nozzles)
- Nozzle width if 2D
- Station 6 Mach number or cross-sectional area
- Station 6 total pressures and temperatures, fuel/air ratio, hot gas mass flow
- Station 16 coolant temperature
- Station 8 total pressure and temperature
- Ambient pressure and temperature

A description of each station in the exhaust system is shown in Fig. 3.



Station	Description		
6	Start of screech liner		
7	End of augmentor		
7.5	End of transition duct		
8	Throat		
9	Nozzle exit plane		
16	Coolant at Station 6 plane		

Figure 3. Exhaust System Station Description

From these inputs, the code calculates the internal gaspath pressures and temperatures based on one-dimensional, isentropic flow. In this manner, the required user input is kept to a minimum so that the objective of user-friendliness is achieved. For the internal aerodynamic calculations, the following assumptions are made:

- The flow is sonic at the nozzle throat and is supersonic thereafter.
- The divergent section of the nozzle is flowing fully with no flow separations (isentropic expansion aft of the nozzle throat).
- The 1D aero routine does not account for addition of the exhaust system coolant massflow, \dot{m}_{16} , into the hot gas. Rather, the 1D aero routine calculates a Mach / pressure / temperature profile within the exhaust system based on the hot gas massflow only.
- For 2D nozzles, the divergent flaps and sidewalls are rectangular in shape. Upper and lower divergent flaps are the same length and symmetric about the engine centerline.

B. Thermal Approach

The goals of the development of LinerTherm[™] were to create a user-friendly and accurate method of performing the thermal analysis of air-cooled liners. User-friendliness was developed into the code through use of intuitive GUIs for input and output control. By making the interfaces intuitive, training and complicated manuals are not required. The code accuracy was addressed through use of the architecture summarized in Fig. 4. Although this architecture specifies use of a flow model, the current version of LinerTherm[™] omitted the flow model in favor of a fixed backflow margin approach. The fixed backflow margin offers the advantage of improved ease-of-use while analyzing the "ideal" solution. That is, by using a fixed backflow margin, the user does not need to input the details of a complex flow circuit. This is considered the "ideal" solution since a fixed backflow margin provides uniform flow throughout the liner. The addition of a flow model adds "real" effects, resulting in increases to the required cooling flow. Of course, the liner designer's goal is to design a liner as close to ideal as possible, considering weight and cost impacts. As shown in Fig. 4, the "cooling analysis" portion of the code incorporates models for radiation, conduction, convection, impingement, effusion, film effectiveness, and film superposition. From these, a heat balance is performed, considering the heat-up of the coolant. This approach provides a highly accurate solution for the liner temperature and flow requirements.



Figure 4. Basic Logic Architecture of LinerThermTM

As illustrated in Fig. 5, an electrical analogy may be applied to solving the thermal equations of advanced cooling systems. This figure shows a simple cooling circuit where thermal resistances, including conduction, convection, and radiation, are modeled. This analysis is performed at multiple axial locations to provide a detailed wall temperature distribution.



Figure 5. Electrical Analogy Applied to Cooling Liner Analysis

C. Impingement

Impingement cooling provides high intensity heat transfer of large surface areas through the use of an array of closely spaced jets impinging normal to the surface from a perforated parallel plate placed close to the surface. Florschuetz, et al.¹ have correlated experimental results of impingement jets on a flat surface with and without crossflow. These correlations provide the basis of the impingement methodology in LinerThermTM.



Figure 6. Impingement Cooling Scheme

D. Hot Gas Convection with Multi-hole and Slot Film Cooling

1. Film Cooling Methodology

The convective heat flux in a film-cooled environment is determined by replacing the adiabatic wall temperature with the film temperature, as follows:

$$q = h_g \left(T_{aw,f} - T_{wall} \right) \tag{2}$$

The film temperature is calculated from the film effectiveness, as shown below:

$$\eta = \frac{T_{aw} - T_{aw,f}}{T_{aw} - T_{cool}} \tag{3}$$

The film effectiveness η varies with both the distance from the point of injection and the coolant flow rate, and is generally based on empirically-derived correlations. These correlations have generally been found to be functions of the non-dimensional parameter x/MS, where x is the distance from the injection location, S is the slot height, and M is the blowing ratio (as defined below).

$$M = \frac{(\rho V)_{cool}}{(\rho V)_{gas}} \tag{4}$$

2. Film Superposition

LinerThermTM accounts for nonlinear film superposition from upstream rows of holes or slots. Superpositioning of multiple film injection rows involves the addition of the effect of each successive row to determine the resulting film-adjusted adiabatic wall temperature. The method of superposition assumes that the film temperature for any slot (or rows of holes) can be determined by replacing its gas adiabatic wall temperature with the film temperature from the previous slot. This process is applied in a stepwise manner in the axial direction of the mainstream flow to obtain a film temperature profile over the entire cooled surface. The effect of film superposition is illustrated in Fig. 7.

Film effectiveness superposition



Figure 7. Effect of Film Superposition

3. Film Blowoff

Since multi-hole systems inject film at an angle with respect to the mainstream flow, there exists a potential for the film to blow off the surface at high pressure ratios, thereby significantly reducing the film effectiveness downstream of injection. Film blow-off correlations are generally a function of the blowing ratio and angle of injection. Built-in functions have been incorporated into the code, while the option to over-ride these correlations is provided for the user.

4. Effusion

Effusion cooling (also known as full-coverage film cooling or transpiration cooling) is comprised of a large number of small film holes spaced closely together. The tight hole spacing provides a substantial cooling benefit over standard film cooling schemes if film effectiveness superposition is considered. Moreover, in-plane convection from the effusion holes provides an additional benefit as liner thickness is increased, thus providing a larger surface area from which to draw away heat.

Effusion analysis can be cumbersome due to its three-dimensional nature. LinerThermTM approximates the effects of effusion by analyzing convection through a slot with the same flow as the multi-hole configuration. In this manner, the effusion scheme is broken down into a quasi-2D problem.

E. Coolant Temperature Rise

As coolant air travels through the exhaust system, it picks up heat from the exhaust air and its temperature rises accordingly, as shown in Fig. 8.



Figure 8. Coolant Temperature Rise

LinerThermTM performs an energy balance and calculates a coolant temperature rise using one of two methods, depending on the cooling scheme:

- For liner systems with impingement, the energy balance is performed by a radiative heat shield approach, wherein the emissivities of the impingement sheet and backing structure are taken into account.
- For convectively cooled liners, the coolant temperature rise is calculated by a traditional heat exchanger approach, assuming that all of the heat is absorbed by the coolant.

F. Radiation

5. General Theory

A black surface emits radiant energy at a rate proportional to the absolute temperature of the surface raised to the fourth power. Real surfaces, however, are non-black and emit radiation at a rate less than maximum. The emissivity, ε , provides a measure of the radiation as a fraction of the maximum blackbody radiation. According to Lefebvre² and experimental data, the relationship for calculating the radiation from hot exhaust gases to the cooling liner surface may be expressed as follows:

$$q_{rad} = \sigma \left(\frac{1 + \varepsilon_{wall}}{2}\right) \left(\varepsilon_g T_{sg}^4 - \alpha_g T_{wall}^4\right)$$
(5)

where the gas emissivity is defined as:

$$\varepsilon_g = 1 - \exp\left[-3.9 \times 10^4 \, K P_{sg} T_{sg}^{-1.5} \sqrt{L_b \frac{f}{a}}\right] \tag{6}$$

and

$$\begin{split} & \text{K} = \text{luminosity factor} = \text{f}(\text{C/H}) \\ & \text{K} \approx 1.42 \text{ for JP fuel exhaust systems} \\ & \text{P}_{\text{sg}} = \text{local gas static pressure, atmospheres} \\ & \text{L}_{\text{b}} = \text{beam length} = 0.9 \text{ D}_{\text{h}} \text{ (ft)} \\ & \alpha_{g} = \varepsilon_{g} \left(\frac{T_{sg}}{T_{wall}}\right)^{1.5} \end{split}$$

In all areas upstream of the throat, the stoichiometric temperature is used along with a radiative view factor of one. This is a conservative assumption to account for hot streaks in the exhaust flow.

6. Radiation to Ambient in Divergent Section

The exhaust gases in the divergent section radiate not only to the nozzle walls, but to ambient air as well. LinerThermTM accounts for this heat loss using standard radiation view factor relationships between the nozzle surfaces and ambient air.

G. Turbine Exit

In order to maintain simplicity, LinerThermTM assumes the following at the turbine exit:

- 1. The tailcone is conical in shape
- 2. The turbine exhaust case has a constant outside diameter equal to D_6 , and a constant inner diameter along the vanes
- 3. The vanes are straight (no turning), with a semi-circular leading edge and pointed trailing edge
- 4. An impingement/multi-hole film cooling scheme is used on all components (tailcone, vanes, etc.)
- 5. Effusion analysis is not an option, at present, due to the complex geometry
- 6. Vane leading edge (stagnation) heat transfer is not included
- 7. There is no coolant temperature rise within the turbine exit (all coolant temperatures = T_{T16})

Figure 9 shows a graphical representation of the default turbine exit geometry.



Figure 9. Turbine Exit Default Geometry

III. Using LinerThermTM

H. User Interface

The user interface is shown in Fig. 10. Wherever possible, user input requirements have been kept to a minimum. Through selection of user-defined options, the user may select to analyze either an axisymmetric or twodimensional (2D) nozzle. As mentioned, aerodynamic boundary conditions are calculated internally for the engine cycle and geometric inputs. These boundary conditions may be plotted and viewed prior to executing the thermal analysis. Cooling liner types, including impingement, multi-hole film, slot film, or convection, may be selected. Material selection is enabled through simple drop-down menus of materials for each component. Material properties, including max use temperature and conductivity, are automatically defined by the material selection. However, these properties may be over-ridden when desired. Film effectiveness may be selected from a drop-down menu of published correlations or new correlations may be input by the user through use of simple table reads.



Figure 10. User Interface

IV. LinerThermTM Output

LinerThermTM includes a user-friendly output screen, wherein the coolant massflows and maximum surface temperatures of each component are listed. Moreover, the user may plot two parameters as a function of axial location. The default parameters include surface temperature, adiabatic wall temperature, coolant temperature, gasside and coolant-side heat transfer coefficients, film effectiveness, and local heat flux. Cost and weight summaries are also included.



Figure 11. Output Screen

V. Sample Case

Figure 12 shows an example of how LinerThermTM can be used to estimate the optimum impingement hole spacing for a given liner. In this sample case, four test runs were completed with varying impingement hole spacing. The resultant coolant massflow and backflow margin are plotted against the impingement hole spacing. The green box shows the range of impingement hole spacings that meet both coolant massflow and backflow margin criteria. The four test cases took approximately ten minutes to run on a typical Windows XP system.



Figure 12. Trade Study Results

VI. Summary

A heat transfer/thermal modeling code, LinerThermTM, has been developed for rapid detailed analyses of aircraft gas turbine exhaust system liners. The code includes capabilities for impingement, multi-hole film-cooling, slot film-cooling, and convective cooling. Its simple user interface provides the capability to quickly evaluate the impact of key design features. The code provides the user with a tool for performing "what-if" scenarios to evaluate the effects of liner material and geometric selections to determine their impacts on cooling flow requirements and liner weight. In the development of exhaust system liners, trade studies must be performed so that decisions can be made early in the development process. The earlier these critical decisions are made, the greater the savings in development costs. LinerThermTM is a trade study tool that allows critical decisions regarding liner material and geometric selections to be made at an earlier time in the development cycle, thereby saving considerable program cost.

VII. Acknowledgments

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VIII. References

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