ANALYSIS OF THE EFFECTS OF VITIATES ON SURFACE HEAT FLUX IN GROUND TESTS OF HYPERSONIC VEHICLES

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ABSTRACT

To achieve the high enthalpy conditions associated with hypersonic flight, many ground test facilities burn fuel in the air upstream of the test chamber. Unfortunately, the products of combustion contaminate the test gas and alter gas properties and the heat fluxes associated with aerodynamic heating. The difference in the heating rates between clean air and a vitiated test medium needs to be understood so that the thermal management system for hypersonic vehicles can be properly designed. This is particularly important for advanced hypersonic vehicle concepts powered by air-breathing propulsion systems that couple cooling requirements, fuel flow rates, and combustor performance by flowing fuel through sub-surface cooling passages to cool engine components and pre-heat the fuel prior to combustion. An analytical investigation was performed comparing clean air to a gas vitiated with methane/oxygen combustion products to determine if variations in gas properties contributed to changes in predicted heat flux. This investigation started with simple relationships, evolved into writing an engineering-level code, and ended with running a series of CFD cases. It was noted that it is not possible to simultaneously match all of the gas properties between clean and vitiated test gases. A study was then conducted selecting various combinations of freestream properties for a vitiated test gas that matched clean air values to determine which combination of parameters affected the computed heat transfer the least. The best combination of properties to match was the free-stream total sensible enthalpy, dynamic pressure, and either the velocity or Mach number. This combination yielded only a 2% difference in heating. Other combinations showed departures of up to 10% in the heat flux estimate.

INTRODUCTION

In the early development of supersonic combustion ramjet flowpaths, the focus of the research was generally based on developing the combustor design, injection strategies, and flameholders needed to achieve sustained, robust supersonic combustion across a range of Mach numbers. Heat loads in ground tests were typically managed through the use of thermally-conductive heat-sink hardware and relatively short test times. In these tests, thermal analysis of the hardware was generally limited to ensuring survivability of the hardware. The hardware could typically be oversized, providing sufficient margin for any errors introduced by analytical assumptions.

Since many envisioned future hypersonics systems require long duration flight, attention must be paid to active cooling as a strategy to mitigate large aerothermal loads. One concept is to use the fuel as a cooling medium. This is a benefit to hydrocarbon fueled engines since the cooling process pre-heats the fuel which aids the ignition and combustion process. This approach results in a coupling of surface heating rates, fuel flow rates, fuel ignition and burning properties, and to some degree, vehicle performance and operation. This coupling increases the need to accurately estimate flight surface heating rates from both computational models and ground based tests.

To mitigate some of the uncertainty in engine and vehicle performance at hypersonic speeds, components, engines, and whole vehicles (when possible) are tested in ground test facilities before progressing to atmospheric flight. To achieve the high enthalpy conditions associated with hypersonic flight, many hypersonic ground test facilities burn fuel in the test gas upstream of the test chamber. Typically for air-breathing propulsion testing, the

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oxygen consumed by combustion is replenished to produce a test gas with an oxygen mole fraction equal to that of atmospheric air. Unfortunately, the products of combustion contaminate the test gas, resulting in a vitiated test medium with altered gas properties and the heat fluxes associated with aerodynamic heating. Since it is not possible to match all of the properties simultaneously, the question arises as to which properties should be matched between the ground tests and flight. The preferred combination of properties may vary with discipline, analysis method, and/or the goals of the ground test. For example, Mach number, total temperature, and total pressure may be preferred by a facility engineer since they are closely related to the operation of the facility, whereas the conserved properties are the natural variables to be used when conducting a one-dimensional flow analysis. Similarly, the combination of properties may be different if the goal of the ground test is thrust versus thermal loading. This paper will examine how contaminates affect test gas properties and surface heat fluxes, and will focus on which combination of properties yield the best match of heat flux between ground and flight. While a large variety of fuels can be used in combustion heated facilities, the gas composition in this paper will be limited to that for a methane-fueled facility with oxygen replenishment.

LITERATURE SURVEY

A number of reports of aeroheating tests performed in vitiated test gas were reviewed. Most of these tests were performed in the NASA Langley Research Center 8-Foot High Temperature Tunnel (8-Ft HTT) which is a methane vitiated facility, before the tunnel was modified for oxygen replenishment to accommodate air-breathing propulsion testing. Several of the papers reviewed compared results obtained in both vitiated test media and clean air. These reports included a variety of test articles such as flat plates[1], bodies of revolution[2,3], thermal protection systems[4], structural tests of engine components[5-8], and shock/shock interaction on leading edges[9-11] as well as methods to calculate the flow and transport properties of vitiated test gases[12-14]. Most of the reports do not discuss any effect of the test medium on the results. The few reports that do directly address the difference indicate that any difference appears to be within the data scatter. For example, the work by Weinstein[2] sought to determine if air containing methane/oxygen combustion products affected the pressure distribution for hemispherical cylinders at Mach 7 conditions typical of hypersonic vehicles. The estimated variation in the absolute stagnation pressure between the tunnel test gases and clean air was determined to be about 2%. No direct comparison of the heat transfer rate (between the vitiated test medium and clean air) was made.

In reviewing the literature, there was at least one exception to the assumption that clean air and a vitiated test gas behaved similarly when considering thermal effects: the Type IV shock/shock interaction in vitiated test gas, as reported in references 10 & 11. Wieting noted that the peak heating rates in the jet impingement zone were significantly less than those in the clean air levels. He attributed this to the variation of the specific heat with static temperature through the shock layer causing a wider jet to form in the Type IV shock/shock interaction in the vitiated case. By suggesting that caloric imperfections are important in the heat transfer estimate, an accounting of the specific heat for each participating species must be considered. Although this exception was important to note, it did not quantify the contribution of gas properties to variations between the test media.

A review of flight data from the Hyper-X Program yielded no additional insight into this issue. Since the thermal design of the X-43 engine managed heat loads though the use of heat-sink copper, no detailed comparison of heating rates between wind tunnel and flight engines was performed.

BASELINE CONDITIONS

With a scarcity of data in the literature to quantify heat flux measurements in vitiated test media, it was determined that an analytic effort would be in order. Baseline conditions were established that are representative of test conditions in a facility that burns methane in oxygen enriched air, such as the 8-Ft HTT, to obtain the high enthalpy levels of hypersonic flight. A Mach 5 test point was selected and is presented in Table 1. The mole fractions for the individual species that define the clean air model are presented in Table 2. A wall temperature of 477.8K was specified for all analysis in this study.

Table 1. Baseline Case (Clean Air Model)

Property	Baseline	Units
Mach Number	5.00	-
Velocity	1455.0	m/s
Static Temperature	210.5	K
Total Temperature	1192.2	K
Static Pressure	6559.6	Pa
Dynamic Pressure	114.9	kPa
Total Pressure	3785.2	kPa
Total Sensible Enthalpy (T_{ref} = 0.0 K)	1270.0	kJ/kg
Specific Heat	1002.5	J/(kg-K)
Specific Heat Ratio	1.401	-
Wall Temperature	477.8	K

Table 2. Clean Air Mole Fractions

Species	Mole Fraction
N_2	0.78088
O_2	0.20950
CO_2	0.00030
Ar	0.00932

For the purposes of this paper, total sensible enthalpy is defined by:

$$h_{total\_sensible} = \int_{T_{ref}}^{T} c_p dT + \frac{V^2}{2} \tag{1}$$

where the reference temperature, T_{ref}, is 0.0K.

To simulate the 8-Ft HTT vitiated test gas, H_2O and CO_2 (products of methane/oxygen combustion) must be added to the clean air model. The proposed vitiated test gas model (Table 3) is based on a chemical equilibrium calculation of the facility gases taken from an actual Mach-5 tunnel operating condition.

Table 3. Vitiated Test Gas Mole Fractions

Species	Mole Fraction
N_2	0.63816
O_2	0.21120
CO_2	0.04767
Ar	0.00764
H_2O	0.09533

HEAT TRANSFER AND GAS PROPERTIES

CONVECTION MODEL

As a first step, examination of gas properties with a simple convection model will provide insight into which parameters have the greatest effect on the heat transfer rate. Convection heat transfer is defined by the following equation:

$$Q_{convection} = h \cdot A \cdot \Delta T \tag{2}$$

where A is the area, ΔT is the difference between the wall temperature and the gas temperature, and h is the heat transfer coefficient. An accurate determination of h requires knowledge of fluid properties, flow speed, wall geometry, and surface condition. Empirical relationships between heat transfer coefficients and fluid flow properties such as Nusselt number can be found in many textbooks. For turbulent forced convection over a flat plate the Nusselt number is determined by the following equation[15]:

$$Nu_x = \frac{h \cdot x}{k} = 0.0288 \cdot \mathrm{Re}_x^{0.8} \cdot \mathrm{Pr}^{0.333} \tag{3}$$

where, $\mathrm{Re}_x = \frac{\rho \cdot V \cdot x}{\mu}$ is the Reynolds number and $\mathrm{Pr} = \frac{\mu \cdot c_p}{k}$ is the Prandtl number. Here, ρ is the density, V is the flow velocity, x is the distance from the leading edge of the plate to a specified location, μ is the absolute viscosity, c_p is the specific heat at constant pressure, and k is the thermal conductivity. The leading coefficient in the equation for Nu_x is empirically determined. Gas properties were computed using the Gordon & McBride curve fits[16] and were evaluated at the film temperature of the gas which is defined as the average of the freestream and wall temperatures. The benefit of this approach is that the dependency of the gas properties on heat transfer rate can be followed. Starting from the baseline conditions, the Mach number, freestream temperature, and freestream pressure were matched to produce heat transfer rates at the 1.52m location. The results (Tables 4a & 4b) showed that for the baseline static temperature (case 1), a decrease in the heat transfer rate occurred due to the presence of H_2O and CO_2. This trend was also true as the static temperature was increased, as can be seen in cases 2-4. Table 4c lists the variance between the two gas combinations. For the purpose of this paper, variance is defined as the difference between the values of vitiated test gas and clean air gas divided by the clean air value.

At these conditions, the presence of vitiates results in a lower overall heat transfer rate of roughly 4%. An examination of the total sensible enthalpy for the two gas models shows a slight difference since the Mach number, static temperature, and static pressure were held constant while allowing all other flow parameters to vary. From this simple analysis it is not clear why there is a difference in the heat transfer rate between the two gases; however, an examination of the speed of sound and thermal physical and transport properties provides some additional insight.

Table 4a. Clean Air Heat Transfer Rates

Case	Static Temp [K]	Static Pressure [Pa]	Static Density [kg/m^3]	Wall Temp [K]	Mach # [-]	Total Sens. Enthalpy [kJ/kg]	Clean Air Heat Transfer Rate [W/cm^2]
1	210.5	6559.6	0.1085	477.8	5	1270.0	10.26
2	600	6559.6	0.0381	477.8	5	3570.2	38.35
3	900	6559.6	0.0254	477.8	5	5275.5	54.24
4	1200	6559.6	0.0190	477.8	5	6977.6	68.30

Table 4b. Vitiated Test Gas Heat Transfer Rates

Case	Static Temp [K]	Static Pressure [Pa]	Static Density [kg/m^3]	Wall Temp [K]	Mach # [-]	Total Sens. Enthalpy [kJ/kg]	Vitiated Test Gas Heat Transfer Rate [W/cm^2]
1	210.5	6559.6	0.1078	477.8	5	1277.0	9.89
2	600	6559.6	0.0378	477.8	5	3567.4	36.84
3	900	6559.6	0.0252	477.8	5	5274.8	52.22
4	1200	6559.6	0.0189	477.8	5	6981.5	65.86

Table 4c. Variance between Clean Air and Vitiated Test Gas Heat Transfer Rates

Case	Clean Air Heat Transfer Rate [W/cm^2]	Vitiated Test Gas Heat Transfer Rate [W/cm^2]	Variance [percent]
1	10.26	9.89	–3.61
2	38.35	36.84	–3.94
3	54.24	52.22	–3.72
4	68.30	65.86	–3.57

SPEED OF SOUND

One of the benefits of a simple model involving a correlation is that individual parameters can be easily interrogated to determine what factors contribute the most to variations in heat flux. To further illustrate this point, the gas temperature was held constant in the evaluation of the speed of sound for both gas models (clean air and vitiated test gas) and for all of the gases that comprise the two gas models. The speed of sound, a, is defined as:

$$a = \sqrt{\frac{\gamma \cdot R_{univ} \cdot T}{MW}} = \sqrt{R_{univ} \cdot T} \cdot \sqrt{\frac{\gamma}{MW}} \qquad (4)$$

where, γ is the ratio of specific heats, R_{univ} is the universal gas constant, T is the gas temperature, and MW is the molecular weight. When comparing gases at the same temperature, only the ratio (γ/MW) changes. Table 5 shows the speed of sound for each species. The values for γ and MW of CO_2 and H_2O are significantly different from those for the aggregate clean air and the vitiated test gas. It is interesting to note that those large variations do not show up in the aggregate vitiate speed of sound results. When vitiates are added to the clean air model, the increase in the speed of sound by the H_2O contribution is offset by the added CO_2 contribution (which has a lower speed of sound) and by the reduced mole fraction of N_2 (which has a higher speed of sound). The result of vitiation on the speed of sound is therefore negligible. This result is fortuitous, for if the products of vitiation were solely H_2O or CO_2, the resultant speed of sound would be significantly different.

Table 5. Speed of Sound for Various Gas Mixtures

Species	*MW* [kg/kmol]	γ [non-dim]	γ/*MW* [kmol/kg]	*a* [m/sec]
Clean Air	28.964	1.398	0.0483	372
Vitiated Test Gas	28.756	1.381	0.0480	371
Pure N_2	28.013	1.399	0.0499	378
Pure O_2	31.999	1.390	0.0434	353
Pure Ar	39.948	1.667	0.0417	346
Pure CO_2	44.010	1.270	0.0289	287
Pure H_2O	18.015	1.326	0.0736	459

Evaluated at T_{film} = 344.2K

THERMAL PHYSICAL AND TRANSPORT PROPERTIES

Some of the thermal physical and transport properties of the species that make up the gases in this study are presented in Table 6. For the baseline conditions, a breakout of the gas properties (evaluated at T_{film} = 344.2K) shows that the presence of H_2O contributes greatly to the overall specific heat. Additionally, the absolute viscosity and thermal conductivity for H_2O are significantly lower than those for clean air. Both the Prandtl and Reynolds numbers are higher for a pure H_2O atmosphere, which also leads to a higher heat transfer coefficient, *h*.

Table 6. Gas Properties and Heat Transfer Rate for Various Gases

Species	c_p [kJ/kg-K]	μ [kg/m-sec]	k [W/m-K]	Pr [-]	Re [x10^6]	Nu [-]	h [W/cm^2-K]	$T_{recovery}$ [K]	Heat Transfer Rate [W/cm^2]
Clean Air	1.0078	2.060E-05	0.02912	0.713	9.13	9523	0.01819	1042	10.26
Vitiate	1.0475	1.957E-05	0.02806	0.731	9.51	9925	0.01827	1019	9.89
N_2	1.0408	1.987E-05	0.02905	0.712	9.31	9671	0.01843	1037	10.30
O_2	0.9270	2.310E-05	0.02995	0.715	8.53	9028	0.01774	1043	10.03
Ar	0.5204	2.543E-05	0.01991	0.665	9.48	9588	0.01252	1622	14.33
CO_2	0.8893	1.713E-05	0.02008	0.759	12.90	12818	0.01688	916	7.39
H_2O	1.8786	1.126E-05	0.02311	0.916	12.80	13584	0.02058	878	8.24

T_{static} = 210.5 K, T_{wall} = 477.8 K, T_{film} = 344.2 K

RECOVERY TEMPERATURE

To calculate the heat flux, the heat transfer coefficient must be multiplied by a driving potential (a temperature gradient). It should be recalled that the basic mechanism governing aerodynamic heating is the conversion of kinetic energy (from the high speed flow) to heat (through the process of stagnating the flow). If this process could be performed isentropically, the resultant driving potential for convective heat transfer would simply be the total temperature minus the wall temperature. However, since heat is lost (through diffusion) as the flow is brought to rest at the wall, an adjustment must be made to reduce the driving potential. The replacement of the total temperature is found in the recovery temperature which is a function of the static temperature T_{static}, specific heat ratio γ, Mach number *M*, and Prandtl number Pr:

$$T_{recovery} = T_{static} \cdot \left(0.5 \cdot \Pr^{0.333} \cdot \left(1.0 + (\gamma - 1.0) \cdot M^2\right)\right) \tag{5}$$

For the case of H_2O versus clean air, the lower recovery temperature of H_2O offsets the higher heat transfer coefficient, and the resultant heat flux is actually reduced when H_2O is added to clean air. Similarly, CO_2 gas, when added to clean air, reduces the overall heat flux but to a much greater degree.

The benefit of using a simple convection model is that it allows examination of the contributions of individual species that are combined to create an overall heat flux. Inherent in these results is the assumption that the species properties vary only with static temperature. It would appear to be reasonable to assume that in matching the vitiated test gas to clean air, holding static temperature as a constant would be one of the requirements to ensure agreement when determining heat flux.

MATCHING TUNNEL CONDITIONS

As observed in the preceding section, the gas properties between the two gas models are different because the species and the mole fractions are different. This introduces differences, not only in the specific heat, viscosity, and thermal conductivity, but in the overall gas density, velocities, and energy as well. When trying to correlate tunnel results to flight, the question arises as to which of these properties are the best to match. For a one-dimensional flow, two independent properties are required to define the thermodynamic state and one property is required to define the speed of the flow.

There are a number of possible combinations of flow properties. For example, flow energy is often represented by the total enthalpy but can also be represented by the total temperature of the flow. Similarly, one can use either the velocity or the Mach number as a measure of the speed of the flow. In order to determine which combination of properties is best to match, a numerical study was undertaken. Although there are many combinations of variables available for comparison, the parameters that were included in this analysis were limited to one parameter from each of three groups: flow speed (Mach number or velocity), gas energy (static temperature, total temperature or total sensible enthalpy), and gas pressure (static pressure, total pressure or dynamic pressure). From these properties, 12 cases were examined and compared to the baseline clean air case with analytic methods to capture more of the flow physics than was previously done in the initial estimations of the heat transfer rate (Table 7). Vitiated test gas parameters (for cases 1 – 12) that were matched to the clean air model (case 0) are shaded in Table 7. The column entitled ‘Matched Parameters’ were those parameters held fixed for both the clean air and the vitiated test gas models.

Table 7. Clean Air (Case 0) and Vitiated Test Gas (Cases 1-12) Properties

Case	Matched Parameters	Mach # [-]	Velocity [m/s]	T_{static} [K]	T_{total} [K]	P_{static} [Pa]	P_{total} [kPa]	DP [kPa]	H_{total} [kJ/kg]
0	Clean Air	5.000	1455.0	210.5	1192.2	6559.6	3785.2	114.9	1270.
1	M, T_{total}, P_{total}	5.000	1487.6	220.3	1192.2	5916.5	3785.3	102.8	1336.
2	M, T_{total}, P_{static}	5.000	1487.6	220.3	1192.2	6559.6	4196.7	113.9	1336.
3	M, $T_{total,}$ DP	5.000	1487.6	220.3	1192.2	6615.1	4232.2	114.9	1336.
4	M, H_{total}, P_{total}	5.000	1450.3	209.3	1139.2	5997.9	3785.0	104.2	1270.
5	M, H_{total}, P_{static}	5.000	1450.3	209.3	1139.2	6559.6	4139.4	114.0	1270.
6	M, $H_{total,}$ DP	5.000	1450.3	209.3	1139.2	6615.1	4174.5	114.9	1270.
7	M, $T_{static,}$ P_{total}	5.000	1454.3	210.5	1145.0	5989.8	3785.7	104.1	1277.
8	M, T_{static}, P_{static}	5.000	1454.3	210.5	1145.0	6559.6	4145.8	114.0	1277.
9	M, $T_{static,}$ DP	5.000	1454.3	210.5	1145.0	6615.1	4180.9	114.9	1277.
10	V, H_{total}, P_{total}	5.057	1455.0	205.9	1142.0	5601.5	3785.0	99.6	1273.
11	V, H_{total}, P_{static}	5.057	1455.0	205.9	1142.0	6559.6	4432.4	116.6	1273.
12	V, H_{total}, DP	5.057	1455.0	205.9	1142.0	6461.4	4366.1	114.9	1273.

H_{total} = Total Sensible Enthalpy, DP = Dynamic Pressure

From the freestream properties, the freestream mass, momentum, and energy fluxes were also determined for the clean air model and for each of the vitiated test gas matched parameter sets (see Table 8). The flux variance was defined as the difference between the vitiated test gas flux and clean air flux divided by the clean air flux. The Root-Mean-Square (RMS) was defined as the square root of the sum of the squares of each of the flux variances. Note that the selection of the velocity, total sensible enthalpy and dynamic pressure (case 12) was identical to matching the conserved variables (and conserved fluxes) as found in the formulation of the conservation of mass, momentum and energy equations. Theoretically, the RMS value of case 12 is zero, but the value in Table 7 is nonzero because properties were only matched to three significant digits. It was also noteworthy, that any pairing of total pressure yielded the most RMS variation.

Table 8. Mass, Momentum, and Energy Fluxes

Case	Matched Parameters	Clean Air			Vitiate Test Gas			Variance [%]			RMS
		ρU	**$\rho U^2 + P$**	**ρUH**	**ρU**	**$\rho U^2 + P$**	**ρUH**	**ρU**	**$\rho U^2 + P$**	**ρUH**	**[%]**
1	M, T_{total}, P_{total}	157.9	236.4	200.6	138.2	211.4	184.6	–12.52	–10.54	–7.97	18.2
2	M, T_{total}, P_{static}	157.9	236.4	200.6	153.2	234.4	204.7	–3.02	–0.82	2.03	3.73
3	M, T_{total}, DP	157.9	236.4	200.6	154.5	236.4	206.4	–2.20	0.02	2.90	3.64
4	M, H_{total}, P_{total}	157.9	236.4	200.6	143.7	214.4	182.5	–9.00	–9.27	–9.00	15.8
5	M, H_{total}, P_{static}	157.9	236.4	200.6	157.2	234.5	199.6	–0.48	–0.78	–0.48	1.04
6	M, H_{total}, DP	157.9	236.4	200.6	158.5	236.5	201.3	0.36	0.06	0.36	0.51
7	M, T_{static}, P_{total}	157.9	236.4	200.6	143.1	214.1	182.8	–9.38	–9.40	–8.88	16.0
8	M, T_{static}, P_{static}	157.9	236.4	200.6	156.7	234.5	200.2	–0.77	–0.78	–0.21	1.12
9	M, T_{static}, DP	157.9	236.4	200.6	158.1	236.5	201.9	0.08	0.06	0.64	0.65
10	V, H_{total}, P_{total}	157.9	236.4	200.6	136.9	204.7	174.3	–13.34	–13.37	–13.11	23.0
11	V, H_{total}, P_{static}	157.9	236.4	200.6	160.3	239.8	204.1	1.48	1.44	1.75	2.71
12	V, H_{total}, DP	157.9	236.4	200.6	157.9	236.2	201.0	–0.04	–0.08	0.23	0.24

Units: mass flux [kg/(m^2-sec)], momentum flux [(kN-sec)/(m^2-sec)], energy flux [MJ/(m^2-sec)]

VITIATION QUANTIFIED

CALIPER

To support this effort, a computer program entitled "CALIPER, - CALorically ImPerfect Energy Rates" was written which calculates pre-shock and post-shock conditions for flat plates, wedges, and blunt stagnation regions for gases composed of N_2, O_2, CO_2, H_2O, CO, and Ar. The code assumes that the gas is thermally perfect, allowing specific heat, absolute viscosity, and thermal conductivity to vary with temperature. The code integrates both the enthalpy and pressure over the temperature range of interest to create total conditions. This is necessary as calorically perfect gas relations are not accurate when specific heat varies with temperature. The code utilizes the Gordon-McBride 2002 Thermodynamic Properties curve fits[16] which provides specific heat, enthalpy, absolute viscosity, and thermal conductivity for individual species up to 20,000K. Stagnation heating is evaluated using the Sutton and Graves formulation[17] which compares well with the better recognized Fay-Riddell correlation for clean air. For gases other than clean air, Sutton and Graves is more appropriate since it can estimate heat transfer rates for any gas mixture as long as the collision integral information is available. Heat fluxes for flow over a wedge are evaluated with the reference enthalpy method which corrects for the presence of the boundary layer with a modified Reynolds number in the calculation of the skin friction[18].

STAGNATION HEATING

The first assessment using the CALIPER code examined stagnation heating of a 1.0 centimeter cylinder at the baseline conditions with a wall temperature of 477.8K. The study gases (Tables 2 and 3) were used to compare clean air to vitiated test gas. From Table 9, 12 combinations of matched parameters were examined and then compared against clean air. The results showed that there can be a significant variance between the two gases in the determination of the heat transfer rates if different parameters were matched. Cases 1, 8, 9, 11, and 12 had variances of about –3% or less. The smallest variance came from matching the total temperature and total pressure with Mach number (case 1). Cases 4, 7, and 10 had variances larger than –7%, with case 10 approaching –10%. This worst case resulted from matching the total sensible enthalpy, total pressure, and velocity. It is also interesting to note that two cases (2 and 3) showed a higher heat transfer rate than clean air, as indicated by the positive sign of the variance.

Table 9. Vitiated Test Gas Stagnation Heating Rates Compared to Clean Air

Case	**Matched Parameters**			**Clean Air W/cm^2**	**Vitiates W/cm^2**	**Variance %**
1	Mach #	T_{total}	P_{total}	91.3	90.6	–0.75
2	Mach #	T_{total}	P_{static}	91.3	95.4	4.48
3	Mach #	T_{total}	DP	91.3	95.7	4.92
4	Mach #	H_{total}	P_{total}	91.3	83.9	–8.00
5	Mach #	H_{total}	P_{static}	91.3	87.8	–3.86
6	Mach #	H_{total}	DP	91.3	88.1	–3.40
7	Mach #	T_{static}	P_{total}	91.3	84.7	–7.21
8	Mach #	T_{static}	P_{static}	91.3	88.6	–2.99
9	Mach #	T_{static}	DP	91.3	89.0	–2.49
10	Velocity	H_{total}	P_{total}	91.3	82.4	–9.70
11	Velocity	H_{total}	P_{static}	91.3	89.1	–2.31
12	Velocity	H_{total}	DP	91.3	88.6	–3.07

WEDGE FLOW

The next set of calculations examined turbulent heating for wedge flow. The geometry and flow conditions were created from the baseline Mach 5 flow over a 1.52m long flat plate at a 10º angle of attack with an isothermal wall temperature of 477.8K. The results are shown in Table 10. From this analysis, similar trends were found to those of the stagnation results. Variations of –3% or less came from several combinations of parameters (cases 6, 8, 9, and 11). Note that these cases were also among the best for the stagnation heating problem. However, for this problem, case 11 had the smallest variance (–1.82%). Cases 4, 7, and 10 had variances between –10 to –14%. These combinations of parameters also had the highest variances for the stagnation problem which indicates that they should be avoided if matching heat flux rates is important.

COMPUTATIONAL FLUID DYNAMICS MODEL

The final set of calculations involved CFD turbulent flow calculations for the same cases using the VULCAN CFD code. This code is a structured-grid, finite-volume, multiple-species Navier-Stokes solver with a thermally-perfect thermodynamics model[19]. The VULCAN calculations used a grid with 257 points in the stream-wise direction and 129 points in the normal direction. The normal grid spacing had a y^+ less than 1 along the length of the plate for all cases and more than 60 points in the boundary layer at the end of the solution domain. The flowfield was set to turbulent and solved using the k-ω model of Wilcox. The results of both the engineering code and the CFD model are presented in Table 11 for the same parameter combinations. The CFD results showed a variation of between 1.67 to 10.3% with the best combinations (cases 6 and 12) matching the total enthalpy, dynamic pressure, and either the velocity or Mach number. The engineering code had similar trends. For clean air, the difference between the CALIPER and VULCAN runs was 4.9%. Table 12 shows a direct comparison of the engineering and CFD code results. The column labeled “Difference, %” is defined as the CALIPER value subtracted from the VULCAN value divided by their average. Overall, the engineering method is able to match the higher fidelity CFD heating rates to within 2% (on average) with the largest observed variance of 5%.

Table 10. Vitiated Test Gas Wedge Heat Transfer Rates Compared to Clean Air

Case	Velocity or Mach Number	Temperature or Enthalpy	Pressure or Dynamic Pressure	Clean Air [W/cm^2]	Vitiates [W/cm^2]	Variance [%]
1	Mach #	T_{total}	P_{total}	18.09	17.39	–3.87
2	Mach #	T_{total}	P_{static}	18.09	19.00	5.03
3	Mach #	T_{total}	DP	18.09	19.14	5.80
4	Mach #	H_{total}	P_{total}	18.09	16.17	–10.6
5	Mach #	H_{total}	P_{static}	18.09	17.46	–3.48
6	Mach #	H_{total}	DP	18.09	17.58	–2.82
7	Mach #	T_{static}	P_{total}	18.09	16.29	–9.95
8	Mach #	T_{static}	P_{static}	18.09	17.61	–2.65
9	Mach #	T_{static}	DP	18.09	17.74	–1.93
10	Velocity	H_{total}	P_{total}	18.09	15.51	–14.3
11	Velocity	H_{total}	P_{static}	18.09	17.76	–1.82
12	Velocity	H_{total}	DP	18.09	17.53	–3.10

Table 11. Heat Transfer Rate Comparisons of VULCAN and CALIPER Cases

Case	Matched Parameters	CALIPER			VULCAN		
		Clean Air [W/cm^2]	Vitiates [W/cm^2]	Var [%]	Clean Air [W/cm^2]	Vitiates [W/cm^2]	Var [%]
1	M, T_{total}, P_{total}	18.09	17.39	–3.87	17.22	16.71	–2.97
2	M, T_{total}, P_{static}	18.09	19.00	5.03	17.22	18.21	5.74
3	M, $T_{total,}$ DP	18.09	19.14	5.80	17.22	18.99	10.3
4	M, H_{total}, P_{total}	18.09	16.17	–10.6	17.22	15.57	–9.59
5	M, H_{total}, P_{static}	18.09	17.46	–3.48	17.22	16.78	–2.57
6	M, $H_{total,}$ DP	18.09	17.58	–2.82	17.22	17.51	1.67
7	M, T_{static}, P_{total}	18.09	16.29	–9.95	17.22	16.21	–5.88
8	M, T_{static}, P_{static}	18.09	17.61	–2.65	17.22	16.87	–2.05
9	M, $T_{static,}$ DP	18.09	17.74	–1.93	17.22	17.60	2.19
10	V, H_{total}, P_{total}	18.09	15.51	–14.3	17.22	15.46	–10.2
11	V, H_{total}, P_{static}	18.09	17.76	–1.82	17.22	17.63	2.37
12	V, H_{total}, DP	18.09	17.53	–3.10	17.22	17.54	1.84

Table 12. Heat Transfer Rate Differences for VULCAN and CALIPER Vitiated Test Gas

Case	Matched Parameters	CALIPER [W/cm^2]	VULCAN [W/cm^2]	Difference [%]
1	M, T_{total}, P_{total}	17.39	16.71	–3.99
2	M, T_{total}, P_{static}	19.00	18.21	–4.25
3	M, $T_{total,}$ DP	19.14	18.99	–0.79
4	M, H_{total}, P_{total}	16.17	15.57	–3.78
5	M, H_{total}, P_{static}	17.46	16.78	–3.97
6	M, $H_{total,}$ DP	17.58	17.51	–0.40
7	M, $T_{static,}$ P_{total}	16.29	16.21	–0.49
8	M, T_{static}, P_{static}	17.61	16.87	–4.29
9	M, $T_{static,}$ DP	17.74	17.60	–0.79
10	V, H_{total}, P_{total}	15.51	15.46	–0.32
11	V, H_{total}, P_{static}	17.76	17.63	–0.73
12	V, H_{total}, DP	17.53	17.54	0.06

SUMMARY AND CONCLUSIONS

Heat transfer rate predictions in vitiated test media become more important as hypersonic propulsion concepts incorporate fuel as a heat sink alternative to mitigate large aerothermal loads. To understand the differences between a methane-vitiated test medium and clean air, a series of studies was performed. Overall, the analysis indicated that the selection of "matched" properties is important if variations in heat flux are to be minimized. As part of this study, a code, CALIPER, was developed to provide estimates on heating for flat plates, wedges, cones and stagnation regions. CALIPER accelerated the search process for determining which properties yield the best "match" between gas heat transfer rates. It also provided insight into how gas properties contributed to the overall heat flux. An examination of the Nusselt correlation for a flat plate showed that clean air had a 4% higher heat transfer rate than the vitiated test medium. Although the heat transfer coefficient for both gas models was similar, the recovery temperature of the clean air model was higher, resulting in the higher heat transfer rate. The stagnation results showed that depending upon which parameters were matched, variations in the heat transfer rate between the two gas models was between –10 to 5%. The wedge heat transfer rates showed similar trends. VULCAN CFD cases were then run and the results were compared with those from the CALIPER code. The results confirmed that the methane-vitiated test medium could alter the heat transfer rate by as much as –10%. Based on the flux conserved properties assessment (via CALIPER) and the VULCAN CFD results, two combinations of parameters that showed the most promise are the total sensible enthalpy, dynamic pressure and either (1) the velocity or (2) the Mach number. Runs from the VULCAN CFD code confirmed the trends indicated by the engineering code and the small difference between the CALIPER and CFD heat fluxes validated its use as a screening tool.

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