

Shock-Layer Radiation Insights Available Through Flowfield Property Binning

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This paper introduces a method for assessing similarity between available shock-layer radiation measurements and the radiative heating to a vehicle of interest. This method will be referred to as flowfield property binning (FPB). The challenge in developing this approach is that radiometer measurements from a surface normal line of sight, observed radiation measurements of the entire shock-layer from a distance, or measured shock-tube nonequilibrium profiles are notably different geometrically than the radiative flux to a vehicle surface. Therefore, the relative contributions of various regions of the shock-layer to the measurement, and how these relative contributions compare with the radiative heating to a vehicle of interest, are unclear. By tracking the radiation contribution from each flowfield location, and then grouping this contribution based on two local flowfield properties, these geometric differences are removed. This provides a two dimensional group, or bin, distribution that represents the radiation environment in the same format for various types of radiation simulations, such as observed radiation or radiative flux to a vehicle surface. In the limits of optically-thin radiation transport and thermochemical equilibrium flow, the choice of pressure and temperature as the binning flowfield properties is shown to provide a bin distribution that uniquely defines the radiation simulation. This concept is found to be sufficient for establishing similarity between two cases even when the optically-thin radiation transport and thermochemical equilibrium assumptions are not satisfied. A simple metric of comparison between bin distributions from different cases is provided by the histogram intersection algorithm. This algorithm results in a histogram intersection factor (H) between 0 and 1, which represents the fraction of the radiation that is similar between the two cases. Therefore, if H evaluated between bin distributions for two completely different radiation problems is near 1, then they represent essentially the same radiation problem. This means that they depend on the same weighting of various radiation modeling parameters evaluated at the same pressure and temperature. If one of these cases agrees well with a radiation measurement, then the matching bin distributions provide justification for applying this experimental validation to the other case. Even for H values as low as 0.2, the measurement case could be considered relevant if there are no other useful measurements. This approach allows observed radiation measurements to directly inform radiative heating simulations, which allows NASA's past and future investments in observed radiation measurements to directly inform the radiative heating uncertainty or margins for future vehicle design. This FPB approach is also used to determine shock-tube conditions for informing backshell radiative heating simulations, where the normal shock velocity and Lagrangian time from the shock are used for the binning variables instead of pressure and temperature.

Nomenclature

$h\nu$	Energy, eV, equal to $1.2398 \times 10^3 [\lambda(nm)]^{-1}$
H	Histogram intersection factor, which represents the overlap between two bin distributions
$j_{n,k}$	Emission coefficient at line-of-sight location n along line-of-sight k , $W/cm^3\text{-sr-nm}$
E	Equilibrium emission integrated over a given spectral range, $W/cm^3\text{-sr}$
$F_{bin,i,j}$	Normalized contribution of bin i, j to the total radiative flux or intensity
p	pressure, atm
q	Wall-directed radiative flux integrated over a given spectral range, W/cm^2

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s	Distance along a ray, cm
T_{ve}	Vibrational-electronic-electron temperature, K
t_{shock}	Lagrangian time from the shock along a streamline, s
$V_{N,shock}$	Normal shock velocity that a streamline crossed the bow shock, m/s
$\Delta I_{n,k}$	Radiative intensity contribution from the line-of-sight point n along line-of-sight k , W/cm ² -sr
$\Delta \Omega_k$	Solid angle factor for line-of-sight k
$\Delta q_{n,k}$	Radiative flux contribution from the line-of-sight point n along line-of-sight k , W/cm ²
$\Delta s_{n,k}$	distance increment at line-of-sight point n along line-of-sight k , cm
$\kappa_{n,k}$	Absorption coefficient at line-of-sight location n along line-of-sight k , cm ⁻¹
<i>Subscript</i>	
i	bin index
j	bin index
k	Line of sight index
n	Index along a line of sight, where the radiation is computed in the direction of increasing n
<i>Superscript</i>	
bin	Indicates the bin limits for quantities such as T_{ve} and p

I. Introduction

This paper addresses two challenges of utilizing shock-layer radiation measurements to inform the radiative heating uncertainty or margin for a NASA entry vehicle. These two challenges, described in the following paragraphs, led to a convenient framework for interpreting shock-layer radiation simulations, which also has applications beyond addressing these two challenges. The goal of this paper is to present this framework, which will be referred to as flowfield property binning (FPB), and to provide examples of its application.

The first challenge that motivated this work was the goal of using available “observed” radiation measurements [1] to inform the radiative heating uncertainty or margin for future entry vehicles. These measurements consist of a single spectrum emitted from the entire shock-layer and wake, and are referred to as “observed” radiation measurements to distinguish them from measurements of the radiation to the vehicle surface. NASA has made significant investments into obtaining high quality observed radiation measurements of reentry vehicles, such as Stardust, Hayabusa, etc. [2]. While a number of simulations have been performed to compare existing models with the measurements [3–5], no direct link between the observed radiation measurements and reducing the radiative heating uncertainty for future designs has been available. This link is challenging because of the geometric differences between the observed radiation and the radiative heating to the vehicle surface. The radiative heating to the surface is most strongly dependent on the shock-layer directly above the respective surface point, while the observed radiation is dependent on the total flowfield within the measurement field of view. Figure 1 illustrates this difference by presenting examples of the rays required for each of these computations. Even if the simulation tools reproduce the observed radiation measurements within the measurement uncertainty, it is not clear which part of the flowfield is providing the dominant contribution. Therefore, it is difficult to determine the flight condition and surface location for a future vehicle that contains a similar enough radiative environment for the observed radiation measurement to inform the vehicle’s radiative heating uncertainty or margin [6].

The second challenge that motivated this work is determining the most relevant velocities for shock-tube radiation measurements with the aim of assessing the radiative heating to a given location on a flight vehicle surface (for a given trajectory). These shock-tube measurements obtain the post-shock emission profile, as shown in Fig. 2, and are typically obtained in the NASA Ames EAST facility [7, 8]. This challenge is related to the previously developed shock-tube informed (STI) bias approach [9], which provides a method for directly informing radiative heating simulations with shock-tube measurements. This STI bias approach utilizes the reduced normal shock velocity resulting from streamlines crossing the oblique shock away from the stagnation point. Therefore, for surface locations near the forebody shoulder or on the backshell, shock tube measurements at velocities lower than the vehicle’s free-stream velocity provide the most relevant validation data. A goal of this work is to provide an automatic quantitative approach for determining these velocities. In addition to providing target conditions for future shock tube tests, knowledge of this velocity provides insight into the physics that dominate the radiative heating, which are easier to interpret in terms of a normal shock velocity and time from the shock.

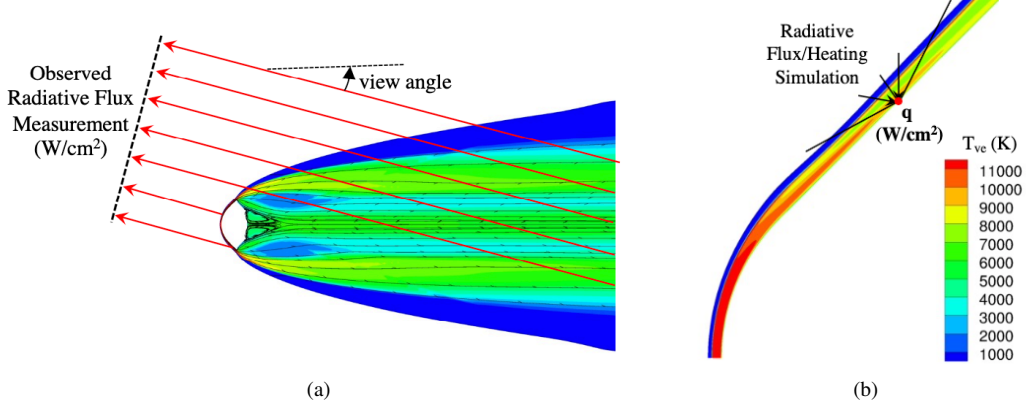


Fig. 1 Comparison between an observed radiation measurement and a radiative heating simulation.

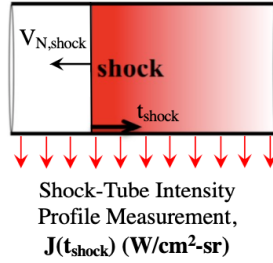


Fig. 2 Schematic of shock-tube radiative intensity profile measurements.

While the two challenges identified in the previous paragraphs may appear unrelated, addressing them has led to a general framework for interpreting shock-layer radiation simulations. This general framework is based on the idea of tracking how much each point in the flowfield contributes to the radiation to a given surface point or to the observed radiation (and in a given spectral range), and then distributing this contribution among a set of groups (or bins) based on the local flowfield properties, such as temperature, pressure, streamline normal shock velocity, etc. The application and justification for this FPB approach is presented in Section II, which also presents a metric of comparison between flowfield property bins called the histogram intersection factor. The simplest application of FPB is presented in Section III for the Fire II stagnation point radiometer, where the single surface normal line of sight simulation is compared with the radiative heating to a Mars Sample Return (MSR) Earth Entry System (EES) case. Section IV then relates a Hayabusa observed radiation simulation to this MSR EES case using FPB. Finally, Section V uses FPB to determine the most relevant shock tube measurements for assessing the backshell radiative heating for a Titan entry case.

II. Overview of the Flowfield Property Binning Concept

The FPB approach is based on the idea that if the radiative flux contribution from various locations in the flowfield can be grouped together based on two sets of local flowfield properties, such as pressure and temperature, then the resulting bin distribution provides a geometrically independent “fingerprint” of the radiative flux. The merit of this bin distribution is that it may be evaluated for simulations of experimental measurements, which may then be compared with the bin distribution from a flight case simulation. The degree of similarity between the measurement case and flight case bin distributions establishes the relevance of the measurement to the flight case. This FPB process is described in subsection II.A, while subsection II.B presents a straightforward approach for comparing bin distributions that results in a single factor H . Subsection II.C provides justification for using flowfield property bins, and the resulting H value, to establish similarity between two cases. Finally, subsection II.D briefly discusses why scaled spectra cannot be used instead of FPB.

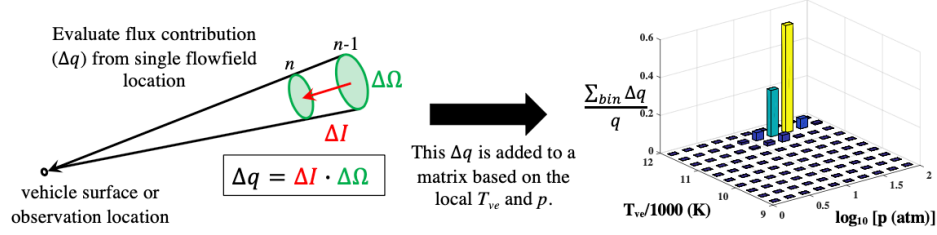


Fig. 3 Overview of the flowfield property binning approach.

A. Evaluation of Flowfield Property Bins

The FPB process is illustrated in Fig. 3. This figure shows that each point in a given flowfield contributes to the radiative flux (to a surface location or external observer location) based on the product of two factors, the change in radiative intensity, ΔI , and the solid angle factor, $\Delta\Omega$. The product of these two factors is the radiative flux increment, Δq , which is written as:

$$\Delta q_{n,k} = \Delta I_{n,k} \Delta\Omega_k \quad (1)$$

where n specifies the location along a line of sight (LOS) and k specifies the LOS. The bin distribution shown on the right-hand side of Fig. 3 is the sum of $\Delta q_{n,k}$ increments at all points n along this LOS, as well as all LOSs k in the field of view of the target location. For a given LOS, $\Delta\Omega$ is constant, while ΔI varies for each point n along the LOS as follows:

$$\Delta I_{n,k} = \left(\frac{j_{n,k}}{\kappa_{n,k}} - I_{n-1,k} \right) \left(1 - e^{-\kappa_{n,k} \Delta s_{n,k}} \right) \quad (2)$$

where $\Delta s_{n,k}$ is the length of this increment, $j_{n,k}$ is the emission coefficient, $\kappa_{n,k}$ is the absorption coefficient, and $I_{n-1,k}$ is the intensity at the previous spatial location (meaning in the direction opposite the intensity computation). The total radiative flux is obtained by summing over all LOS increments n along all LOSs k :

$$q = \sum_{n,k} \Delta q_{n,k} \quad (3)$$

where q is the radiative flux at the target location, which again may be either a surface location on the vehicle or a point external to the shock-layer.

The flowfield property binning approach is enabled by writing q in terms of $\Delta q_{n,k}$, since $\Delta q_{n,k}$ isolates the radiative flux contribution from individual points in the flowfield defined by n and k . This allows $\Delta q_{n,k}$ to be grouped based on the flowfield properties at n and k . Note that the above equations are written assuming a single wavelength value for simplicity, but are applied in practice by integrating Eq. (1) over the wavelength range of interest prior to binning. Also note that for optically thick cases, locations of strong absorption will produce negative $\Delta q_{n,k}$ values.

The grouping of $\Delta q_{n,k}$ into flowfield property bins will be discussed through the remainder of this subsection. To start this binning process, the two flowfield properties for binning must be chosen and the discretization of these properties into a two-dimensional grid must be performed. This discretization requires choosing upper and lower bounds for the binning variables and the number of increments, or bins. Figure 3 shows this grid set up based on $T_{ve}/1000$ and $\log_{10}[p(\text{atm})]$. Both the selection of two dimensions for binning and these two variables, which will be referred to as pressure-temperature binning, will be justified in subsection II.C. The choice of the upper and lower variable bounds depends on the problem, and should be set to capture both forebody and wake contributions. For the present Earth entry cases with pressure-temperature binning, the temperature range of 1,000 to 12,000 and $\log_{10}[p(\text{atm})]$ range of -4 to 0 is sufficient. The choice of the number of bins, or size of each bin, requires a more nuanced discussion because the limits of both a single and infinite number of bins are not appropriate for establishing similarity through FPB. Obviously, a single bin will contain all the radiation and will therefore always compare exactly between cases. Conversely, in the limit of an infinite number of bins, slight differences in flowfield temperatures and pressures will result in no matching bins between two cases that may actually be very similar. Therefore, for the purpose of establishing similarity between two cases using FPB, the bin sizes should not be too large or too small. Instead, the most meaningful bin sizes are chosen so that each bin roughly covers the variable range over which the radiation model is not expected to break down within. In other words, the bins should be large enough that emission from flowfield regions that are ‘close enough’, meaning validation of one is considered validation of the other, are grouped together. This reasoning is based on the goal of

FPB, which is not to show that two cases are exactly the same, only that they are similar enough for the experimental validation of one case to apply to the other. In temperature-pressure space, these increments are chosen as 500 K for temperature and -0.2 for $\log_{10}[p \text{ (atm)}]$, which is based on radiation modeling experience. These bin increments will be used throughout this work, except in Section III, which demonstrates the drawbacks of smaller increments.

To simplify the remaining discussion on constructing bins, pressure-temperature binning is assumed. This pressure-temperature binning is applied for all examples presented in this paper, except for Section V, where Lagrangian time from the shock (t_{shock}) and the normal shock velocity ($V_{N,shock}$) are applied as the two binning variables. The process of binning to t_{shock} and $V_{N,shock}$, or any other two quantities, is exactly analogous to the pressure-temperature binning presented here with a simple replacement of the variables of interest. Representing the bounds of temperature group i by $T_{ve}^{bin,i}$ and pressure group j by $p^{bin,j}$ allows the binning process to be written as:

$$F_{bin,i,j} = \sum_{T_{ve,n,k} \in T_{ve}^{bin,i}, p_{n,k} \in p^{bin,j}} \frac{\Delta q_{n,k}}{q} \quad (4)$$

which simply means that if $T_{ve,n,k}$ is within the bounds of temperature bin i , $T_{ve}^{bin,i}$, and $p_{n,k}$ is within the pressure bin j , $p^{bin,j}$, then $\Delta q_{n,k}/q$ is added to this bin. The normalization of the bin distribution $F_{bin,i,j}$ by the total radiative flux q means that the sum of $F_{bin,i,j}$ over all bins equals unity. The value of this normalization will be discussed in subsection C. Note that the process of evaluating $F_{bin,i,j}$ described in this section is the same for radiative flux to the surface, surface normal intensity, or observed radiative flux computations. These two different computations are distinguished by the choice of LOSs and the solid angle factor $\Delta\Omega$.

B. Metric of Comparison between Flowfield Property Bin Distributions

Once the binning process described in the previous subsection is applied to two cases, the similarity in the radiation simulation between the two cases is assessed by comparing the two bin distributions. To provide a quantitative metric for this comparison, the histogram intersection algorithm developed by Swain and Ballard [10] for image recognition (based on binning pixels and their color) is utilized. This algorithm requires simply taking the minimum value between the two bin distributions at each bin increment (defined by i and j). This is written as:

$$H = \sum_{i,j} \min(F_{bin,i,j}^A, F_{bin,i,j}^B) \quad (5)$$

where A and B distinguish the two cases to be compared, where A could be the simulation of a measurement case and B could be a future flight case simulation. The resulting histogram intersection factor, H , varies between 0 and 1, where 0 indicates that the two bin distributions are completely dissimilar, and 1 indicates the two bin distributions are exactly the same. As the name ‘‘histogram intersection factor’’ suggests, the simple algorithm represented by Eq. (5) computes the intersection, or overlap, of the two bin distributions. Values of H between 0 and 1 represent the fraction of the radiation that overlaps between the two cases. When using the agreement between a measurement and its simulation to inform the radiative heating for a future flight vehicle, this H value may be used to weight the contribution of this measurement comparison to the radiative heating design margin of the vehicle.

For the goal of assessing the similarity between two distributions, this algorithm is superior to other approaches, such as simply evaluating the sum of differences or root-sum-square of the differences between two distributions. These two approaches track the differences between the distributions (instead of the similarity), which results in double counting because the overprediction of one bin will lead to an identical underprediction in another bin. This double counting results in a meaningless comparison factor other than 0 and 1, indicating no agreement or perfect agreement. Another alternative comparison factor that may be considered is the centroid values for the bin pressure and temperature, which may be compared between the two distributions. However, these centroid values provide limited utility because bimodal distributions resulting from forebody and wake emission will result in centroid values that are meaningless to both the wake and forebody emission.

C. Justification for Flowfield Property Binning as a Metric of Similarity

The final step in developing the FPB approach is to justify why similar flowfield property bin distributions indicate that two radiative flux environments are similar. This justification step was saved for last so that the equations and concepts presented in the previous subsections for the binning approach are established. Note that two assumptions

(optically-thin and thermochemical equilibrium) are made in the following discussion. This does not mean that these assumptions are made for any results presented in this work, only that they allow the similarity provided by flowfield property bins to be derived exactly. The validity of this similarity even when these assumptions do not hold will be discussed.

The first assumption made in this discussion is that the radiative flux in the wavelength range of interest is optically-thin. Most radiation measurements are made behind a window or through a long length of atmospheric gas, which means that the more optically-thick vacuum ultraviolet (VUV) region of the spectrum is not captured. Therefore, this assumption is not too restrictive (since the binning process is only applied over the measured wavelength range), even when non-VUV atomic lines or molecular bands may become optically-thick over narrow spectral ranges. The optically-thin assumption implies that $\kappa_{n,k}\Delta s_{n,k} \ll 1$, which simplifies Eq. (2) to the following

$$\Delta I_{n,k} = j_{n,k}\Delta s_{n,k} \quad (6)$$

The valuable consequence of this assumption is that the $I_{n-1,k}$ term in Eq. (2) drops out. This is valuable because now $\Delta I_{n,k}$ is independent of previous points along the LOS, which removes the requirement that the LOS is ordered in a specific manner and makes $\Delta I_{n,k}$ only dependent on the local flowfield properties. Further insight is achieved by assuming the flowfield is in thermochemical equilibrium, which means that $j_{n,k}$ in Eq. (6) is completely defined by the temperature and pressure (assuming a given elemental composition). This allows Eq. (6) to be written as:

$$\Delta I_{n,k} = E(p_{n,k}, T_{ve,n,k})\Delta s_{n,k} \quad (7)$$

where E converts the pressure and temperature to number densities and includes the radiation modeling parameters that convert these number densities to emission coefficients. This E function is the quantity that requires validation when considering radiation modeling. The remainder of this derivation aims to show that the closer a given bin matches between two cases, the closer the relative contribution of E to the total radiative flux becomes, therefore establishing similarity.

Combining Eqs. (1)–(4), the flowfield property bins assuming optically-thin radiation and thermochemical equilibrium are written as:

$$F_{bin,i,j} = \sum_{T_{ve,n,k} \in T_{ve}^{bin,i}, p_{n,k} \in p^{bin,j}} \frac{E(p_{n,k}, T_{ve,n,k})\Delta s_{n,k}\Delta\Omega_k}{q} \quad (8)$$

This equation may be simplified further by recognizing that E , which is only a function of temperature and pressure, is essentially constant for all flowfield points within a given pressure-temperature bin (this becomes exact as the bin spacing becomes infinitely small). This allows Eq. (8) to be written as

$$F_{bin,i,j} = E_{i,j} \sum_{T_{ve,n,k} \in T_{ve}^{bin,i}, p_{n,k} \in p^{bin,j}} \frac{\Delta s_{n,k}\Delta\Omega_k}{q} \quad (9)$$

where $E_{i,j}$ is the nearly constant value of E for bin i, j . This equation shows that when comparing the values of $F_{bin,i,j}$ for two different flowfield cases, the term in the summation is actually the quantity being compared, since $E_{i,j}$ is the same. This summation term can be thought of as the weighting factor for each bin. The key characteristic of Eq. (9) is that this weighting factor is independent of the flowfield properties and radiation model, except for q , which simply scales the bin values so that they sum to 1. Therefore, when the $F_{bin,i,j}$ values match between two flowfield cases, the radiative flux computation of both cases have the same relative dependence on the radiation model, or $E_{i,j}$, evaluated at the bin pressure and temperature. This implies that the radiative flux computations for the two cases require the same relative contribution of E evaluated at a range of temperatures and pressures, and are therefore the same radiation problems. Of course the two bin distributions are not expected to match exactly, and therefore, the H factor defined in Eq. (5) provides a means for quantifying the agreement by taking only the overlapping bin component from the two cases.

Although the thermochemical equilibrium assumption was required for the above derivation, note that this assumption can break down without ruining the utility of the FPB approach. The thermochemical equilibrium assumption was required to make E completely defined by the bin variable of pressure and temperature, therefore allowing the simplification from Eq. (8) to Eq. (9). However, this simplification still holds if flowfield regions where thermochemical equilibrium breaks down only emit strongly for pressure-temperature bins that do not contain significant equilibrium emission. When these equilibrium and nonequilibrium contributions are in separate pressure-temperature bins, the

comparison of the equilibrium bins is justified as discussed. The nonequilibrium bins will result from post-shock nonequilibrium or wake regions, where the contribution from these two regions will also be separate in pressure-temperature space. Numerical experiments show that in the narrow pressure-temperature space that post-shock or wake nonequilibrium bins appear, the assumption that E is uniquely defined by the nonequilibrium pressure and temperature is valid for flowfield regions that contribute noticeably to the radiative flux. In simpler terms, when nonequilibrium regions appear in two bin distributions, they tend to match when they should. Similarly, when only one bin distribution shows a nonequilibrium region, the resulting reduction in H accurately captures the disagreement in the nonequilibrium contribution between two cases. These observations suggest that flowfield property binning remains a valid approach for assessing radiation similarity for cases with moderate nonequilibrium emission. For cases that are completely nonequilibrium dominated, such as Titan or Mars entry cases, pressure-temperature binning is abandoned in favor of Lagrangian time from the shock (t_{shock}) and the normal shock velocity ($V_{N,shock}$). This approach will be discussed in Section V.

D. Spectral Comparisons as an Alternative to Flowfield Property Binning

The previous subsection showed that if optically-thin emission and thermochemical equilibrium is assumed, then matching flowfield property bins between two radiation cases indicates that they are equally dependent on E evaluated at the same pressure and temperatures. Therefore, if one of the cases matches well with experimental data, then the E values at these temperatures and pressures may be considered validated for the other case. While this matching of bins is a promising approach, perhaps there is a simpler method that requires just comparing the scaled spectra between two cases. Given the same assumptions of optically-thin emission and thermochemical equilibrium, can the same similarity established in the previous subsection using FPB be established using comparisons of the scaled spectra, and specifically comparisons of this scaled spectra (scaled spectra means a spectra divided by its frequency integrated value or the spectral range of interest) over a set of frequency integrated spectral ranges? The answer is, no, this similarity cannot be established using the scaled spectra. The reason is that there are an infinite number of different pressure and temperature combinations that can produce nearly identical scaled spectra. For example, consider a case that only has atomic line emission from a single atomic species. If the radiative flux integrated over each atomic line is tracked, and scaled by the total radiative flux, these values will not change with changing pressure for a fixed temperature (assuming thermochemical equilibrium). The changing pressure will change the total radiative flux and the line broadening, but this line broadening will not impact the frequency integrated values for optically-thin cases. These two different pressure cases at the same temperature represent two different radiation problems, since the E values defined in the previous subsection are being evaluated at different pressures, even if the radiation spectra are similar. The flowfield property binning approach would correctly identify these as two different problems, and is therefore a superior approach. Note that although matching scaled spectra do not guarantee matching bin distributions, matching bin distributions do imply that the scaled spectra should match.

III. Application of Flowfield Property Binning for Relating Fire II Radiometer Measurements to EES

Perhaps the most straightforward application of flowfield property binning is narrow view angle radiometer measurements. The narrow view angle, which results from the radiometer sitting deep in a cavity, provides a radiative intensity measurement (in $\text{W}/\text{cm}^2\text{-sr}$) of essentially the normal line of sight from the surface. This is in contrast to a radiative flux (or heating) measurement (in W/cm^2), which captures the intensity integrated over the full field of view. The intensity measurement is simulated by computing only the radiative intensity along the body normal line-of-sight. When applying the flowfield property binning approach in Section IIA to this radiative intensity computation, the $\Delta\Omega$ values in Eq. (1) are equal to 1.0.

To demonstrate the application of the FPB approach to a radiometer measurement, this section considers the Fire II stagnation point radiometer measurement [11] at 1640 s and considers its relevance to a peak radiative heating MSR EES radiative heating simulation. The Fire II vehicle had a free-stream velocity and density of 10.97 km/s and $3.86 \times 10^{-4} \text{ kg}/\text{m}^3$, respectively, while the EES case has a free-stream velocity and density of 10.83 km/s and $5.06 \times 10^{-4} \text{ kg}/\text{m}^3$. The heatshield geometries and relative sizes are compared in Fig. 4.

For brevity, the details of the Fire II radiometer measurements and their comparisons with simulations are not discussed in detail here (see Johnston et al. [12], among others, for details). All that is required for the present discussion is to note the radiometer, which measured the radiative intensity along the body normal LOS, captured only wavelengths

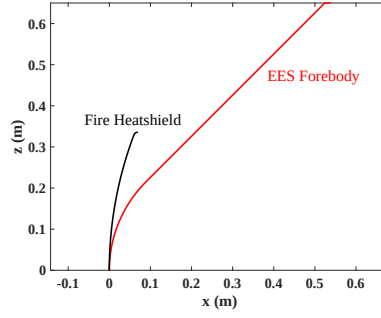


Fig. 4 Comparison of the EES and Fire II heatshield geometries.

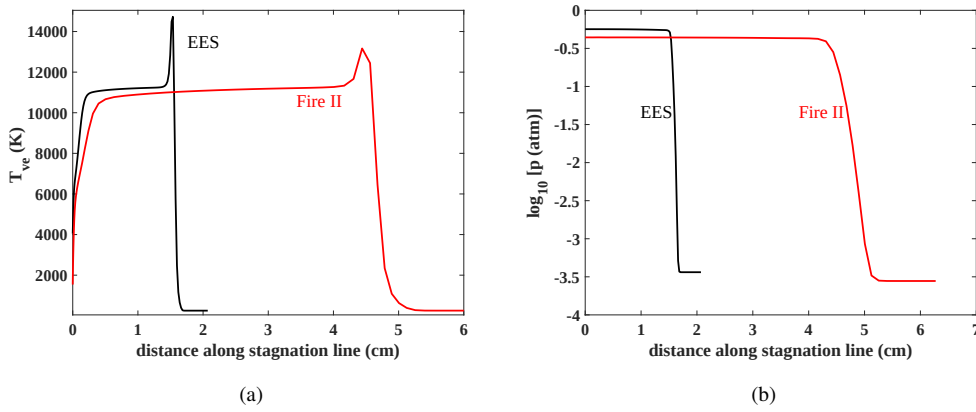


Fig. 5 Comparison of Fire II and EES stagnation line temperatures and pressures.

above 200 nm (or below 6 eV). Furthermore, the present simulations agree with this measurement at 1640 s within 8%, so this case would provide valuable radiative heating validation to the EES case if similarity can be established. Therefore, the goal of this FPB analysis is to assess the relevance of this radiation measured at 1640 s to the stagnation-point radiative heating for EES. FPB is required to make this assessment for three main reasons. The first is that the Fire II case is at a (slightly) different free-stream condition than the EES case, the second is that the Fire II and EES have different geometries, and the third is that the Fire II measurement only considers the normal LOS while the radiative heating to EES considers the entire field of view. Figure 5 illustrates these issues by comparing the stagnation-line temperature and pressure distributions resulting from the two cases. Note that the shock standoff is three times larger for the Fire II case due to the different geometries, and the pressure and temperatures through the shock-layer are different due to the different free-stream conditions. This figure does not show that some of the rays for the EES radiative flux simulation, which are not limited to just the surface normal LOS as the Fire II measurement is, see lower temperature and pressure conditions downstream of the stagnation point. The FPB analysis captures the impact of these downstream regions, which are not included in the simulation of the Fire II measurement.

Figure 6 compares the resulting flowfield property bins in temperature (T_{ve})-pressure space for the Fire II and EES cases. Both cases consider only the radiation above 200 nm to be consistent with the measurements. These bin distributions appear similar, which is confirmed by the resulting H value of 0.88. This H value of 0.88 indicates that only 12% of the radiative heating to the EES stagnation point (above 200 nm) is not captured by the Fire II radiometer. This suggests that the three differences noted in the previous paragraph (different flight condition, geometry, and angular space) are limited to this 12% impact.

To confirm the relevance between the Fire II and EES stagnation point radiation, Fig. 7 compares the radiative intensity spectrum at the stagnation point, normalized by the integrated value above 200 nm (or below 6 eV). While differences are apparent in the spectrum due to line broadening differences (which do not impact the frequency integrated

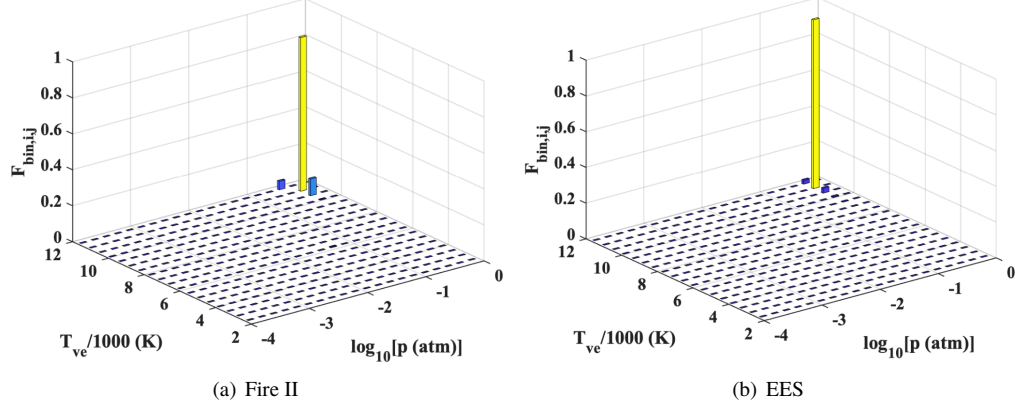


Fig. 6 Comparison of Fire II stagnation point radiometer and EES stagnation point bin distributions.

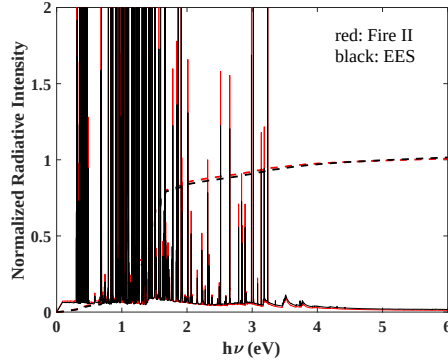


Fig. 7 Comparison of Fire II and EES stagnation line radiation.

value in this essentially optically-thin environment, so are not of interest), the frequency integrated values shown by the dashed cumulative curve show excellent agreement. Recall that, as discussed in Section II.D, this comparison of the normalized spectrum does not provide sufficient insight into the similarity between two radiative environments (because there are infinite combinations of flowfield properties that will produce similar normalized spectra). However, if the H factor between two cases is near 1.0, the normalized spectra should be similar (but not vice versa), as confirmed in Fig. 7.

Note that this analysis used 20 equally spaced bin increments in temperature space ranging from 1,000 to 12,000 K, as well as 20 equally spaced bin increments in logarithmic pressure space ranging from -4 to 0. These relatively wide temperature and pressure ranges are used throughout this work for Earth entry cases, and are chosen to capture both high pressure and temperature forebody emission and low pressure and temperature wake emission, which become important for the cases presented in the next section. For the current stagnation region case, however, this choice of bins may appear to lack sufficient pressure and temperature resolution. To show that this relatively coarse set of bins is actually desired for the present goal of assessing the similarity between a measurement case and a flight vehicle case, as discussed in Section II.A, consider the refined bins presented in Fig. 8. This figure presents the same case as presented in Fig. 6 but with the temperature and pressure ranges greatly reduced while maintaining 20 bins in both directions. Because the stagnation point is considered in this case, the pressure is limited to a narrow range for each case, and these narrow ranges are offset slightly due to the different free-stream conditions, which results in an H value of only 0.3. By considering a trajectory point slightly earlier in the EES trajectory at 10.9 km/s and $4.06 \times 10^{-4} \text{ kg/m}^3$, the EES bins shift to lower pressures, as shown in Fig. 9. These refined bins overlap the Fire II bins with a histogram intersection value of 0.6, while the coarser bins retain the value of 0.88 seen for the nominal trajectory point. This shows that coarser bins prevent slight trajectory variations from impacting H . Since the goal of this analysis is to assess the radiation modeling similarity between the Fire II measurement and EES, and not to show that the cases are necessarily exactly the same, this lower sensitivity of the coarser bins is desired. As discussed in Section II.A, this approximate

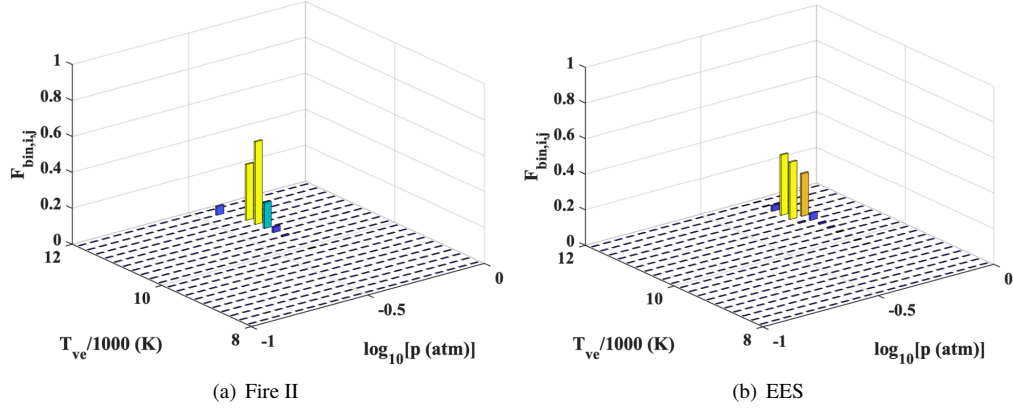


Fig. 8 Comparison of Fire II stagnation point radiometer and EES stagnation point bin distributions with smaller bin increments.

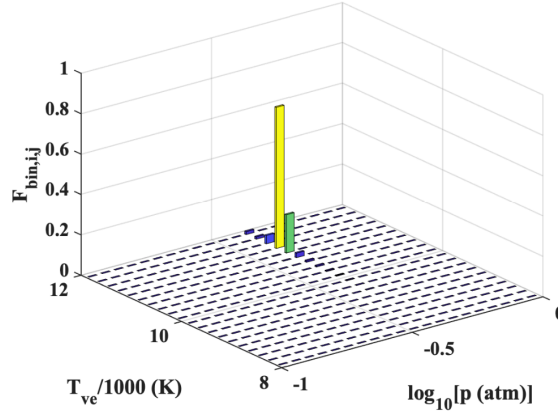


Fig. 9 Refined bin distribution for a slightly different EES free-stream condition.

treatment is acceptable because the radiation modeling is not expected to break down within the range of each coarse pressure-temperature bin, so these larger bins are sufficient for establishing similarity. In other words, the coarser bins provide a more meaningful assessment of the similarity in the radiation modeling than finer bins that require that two cases are nearly identical. Note that this sensitivity to refined bins is exaggerated for this stagnation region case because the dominant temperatures and pressures are limited to a relatively narrow range of values.

IV. Application of Flowfield Property Binning for Relating Observed Radiation Measurements to EES

As discussed in the Introduction, the FPB approach was originally developed to leverage NASA's growing database of observed radiation measurements [1], with the goal to inform the radiative heating uncertainty or margin to future vehicles. This database of measurements includes Stardust, Hayabusa 1, Hayabusa 2 (not yet published), and the upcoming Osiris-Rex entry. Additionally, there are numerous observed radiation measurements of meteors [13, 14], which could be utilized for improving planetary defense modeling.

To demonstrate the application of FPB to observed radiation measurements, with the goal of informing EES radiative heating, this section considers the Hayabusa 1 measurement [15]. The purpose of this section is not to provide a detailed comparison between the measurement and simulation, but rather to demonstrate the relevance of these measurements to EES as an example application of FPB.

The Hayabusa 1 case at 58 km, which is near peak radiative emission, is considered in this analysis [16]. The free-stream velocity and density are 10.7 km/s and $4.4 \times 10^{-4} \text{ kg/m}^3$, respectively. The view angle of the measurement

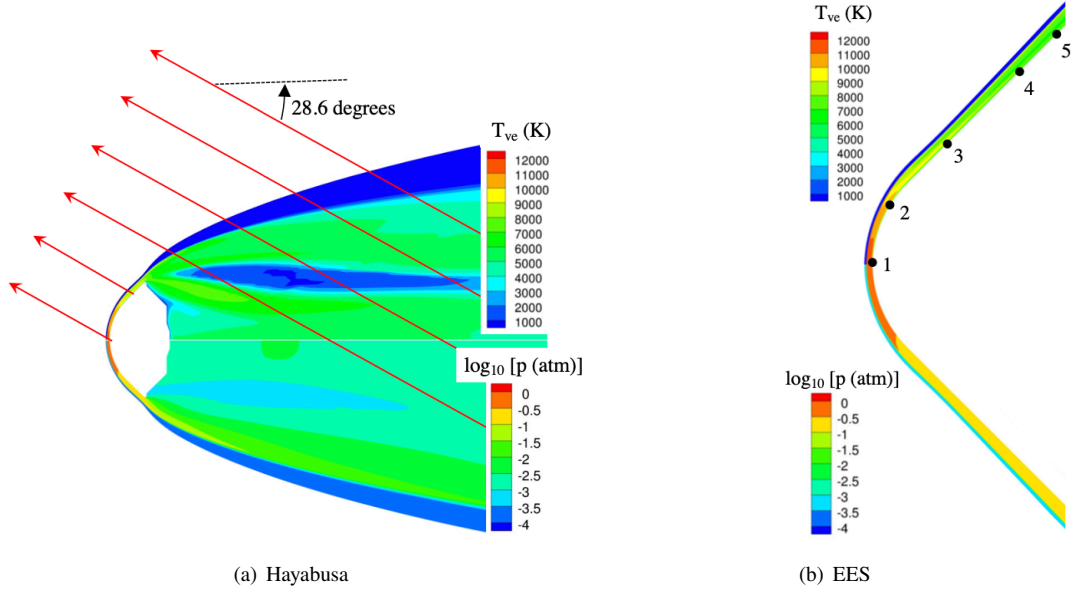


Fig. 10 Comparison of Hayabusa and EES flowfields.

was 28.6 degrees from the capsule's velocity vector. The 700 - 900 nm wavelength range is considered to focus the analysis on the atomic line dominated region of the measured spectrum. Figure 10(a) presents the simulated temperature and pressure profiles through the shock-layer and wake for the Hayabusa case, while Fig. 10(b) presents the same for the forebody shock layer for the EES case. This EES case is the same as that considered in the Fire II analysis (10.83 km/s and $5.06 \times 10^{-4} \text{ kg/m}^3$). The contour bounds in these figures are set to the same bounds as the bin distributions to be presented.

The resulting flowfield property bins for the Hayabusa observed radiation simulations are presented in Fig. 11. Note that this radiation value is the result of over 1000 rays passing through the shock-layer and wake at the view angle, as shown in Fig. 10(a). The shock-layer contribution is clearly represented by the temperatures above 8,000 K and $\log_{10}[p \text{ (atm)}]$ values above -1, while the weak wake contribution is seen below 6,000 K and $\log_{10}[p \text{ (atm)}]$ values below -2.

This Hayabusa simulation produces a radiative flux spectrum that agrees within 30% of the measurement for the strong N and O lines between 700 - 900 nm. To determine how relevant the uncertainty bounds implied by this comparison are to EES at peak radiative heating, the flowfield property bins for radiative heating (between 700 - 900 nm

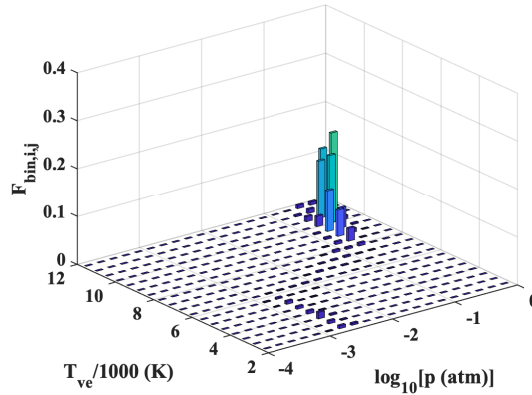


Fig. 11 Flowfield property bins for Hayabusa observed radiation at 58 km.

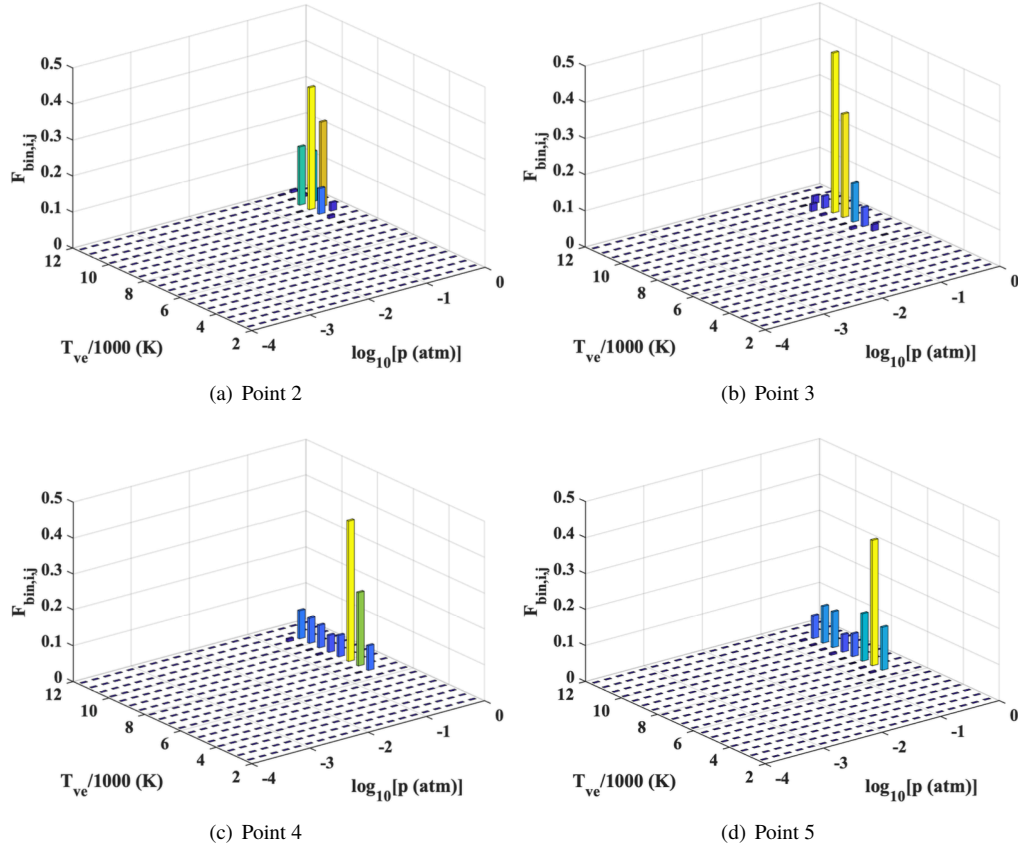


Fig. 12 Flowfield property bins for various EES surface points defined in Fig. 10(b).

to be consistent with the measurement) to four of the five EES surface locations presented in Fig. 10(b) are presented in Fig. 12 (the bins for point 1 were already presented in Fig. 8(b)). These figures show that the bin distributions become more widely distributed in temperature space moving away from the stagnation point. This is clearly apparent moving from point 1 to 2, where point 2 has far more nonzero bins due to its field of view seeing both the stagnation region and milder downstream region. For point 3, the high temperature gas flowing down from the stagnation region provides the dominant radiation. Further downstream at points 4 and 5, this stagnation region gas has dropped below 8,000 K, while the contribution from temperatures near 10,000 K is the result of the post-shock emission of the weaker (than the stagnation region) oblique shock. To explain these distributions more precisely, Fig. 13 compares the surface normal temperature and intensity profiles. Note that the radiative flux requires over 300 of these intensity profiles for a given surface location, but nevertheless these body normal intensity profiles provide useful insight. Assuming these intensity profiles are representative of the radiative flux, the derivative of the intensity profile is the quantity that is binned with temperature and pressure. For example, the constant slope in the intensity for point 2 is centered around 10,000 K, which agrees with the bins shown in Fig. 12(a). Similarly, beyond the small high temperature post-shock contribution, the intensity for point 3 increases at normalized distances between 0.2 and 0.4, where the temperature is around 9000 K. Finally, point 5 shows nearly equal contributions from the higher temperature post shock region and the rest of the lower temperature layer, which explains the large temperature spread of the bins in Fig. 12(d).

The histogram intersection algorithm is applied to quantify the similarity between the EES bin distributions in Fig. 12 and the Hayabusa bin distribution in Fig. 11. The resulting values of H are presented in Fig. 14 for the five EES surface points. This figure shows that surface point 2 has the highest H , with a value of 0.49. This high H factor for point 2 is not surprising based on a rough visual comparison between Figs. 12(a) and 11. Based on analyses of other Hayabusa free-stream conditions, as well as Stardust cases, the maximum values of H seen for observed radiation cases and radiative heating to a surface are no greater than 0.55. This is due to the temperature-pressure bins for the observation cases being oriented essentially diagonally, from low pressure and temperature values to high values. This

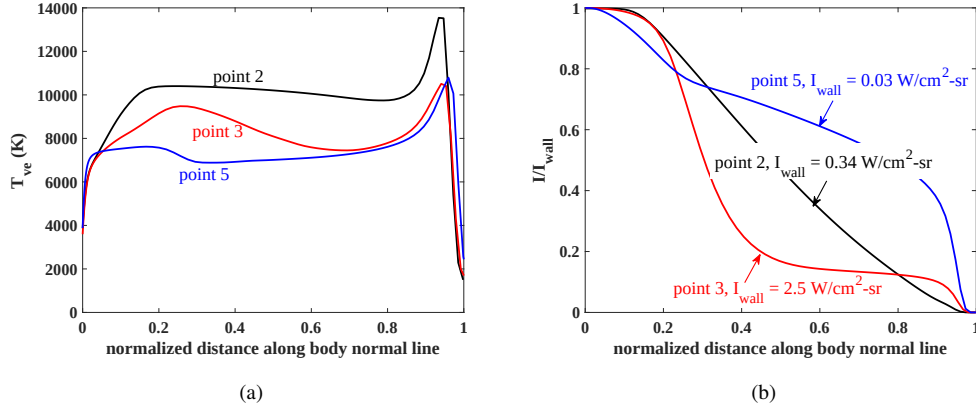


Fig. 13 Surface normal LOS properties for three EES surface points.

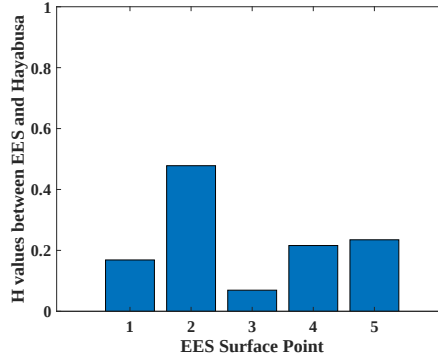


Fig. 14 H factors resulting from comparisons between the radiative heating to various EES surface points and the Hayabusa observed radiation simulation.

distribution is the result of the stagnation region, flank regions, and wake contributing noticeably to the observed radiation. A more exaggerated example of this behavior is seen for the Stardust capsule observation at 42 s. This case is defined by Liu et al. [4] as having a free-stream velocity and density of 12.06 km/s and $5 \times 10^{-5} \text{ kg/m}^3$, respectively, with a view angle of 13.4 degrees. The resulting bin distribution is presented in Fig. 15(a) for the 700 - 900 nm range, which is seen to be strongly diagonal in the pressure-temperature space. For comparison, the resulting bin distributions for an EES case at similar free-stream conditions (11.7 km/s, $6.1 \times 10^{-5} \text{ kg/m}^3$) to Stardust is presented in Fig. 15 for surface point 2. This surface point 2 again provided the largest H of the five surface points, with a value of 0.32. This H value is limited by the EES radiative heating bins varying along temperature but not pressure, and therefore, unable to match Stardust's diagonal distribution.

Once a detailed comparison between Hayabusa and Stardust measurements is performed, which is beyond the scope of this paper, the resulting disagreement factors may be weighted by the H value in the EES, or another vehicle's, margin assessment. This provides a quantitative link between these observed radiation measurements and future flight vehicle design, which has not been available previously. Because of the difficulty and expense of obtaining radiation measurements from radiometers or spectrometers located on a flight vehicle, this is a valuable capability that is enabled by the FPB approach.

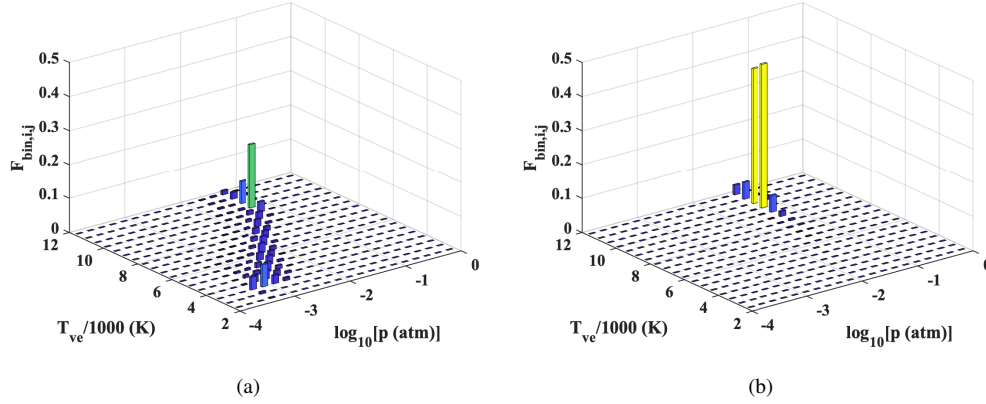


Fig. 15 Comparison of Stardust and EES bin distributions.

V. Application of Flowfield Property Binning to Determining Relevant Shock-Tube Conditions

The shock-tube informed (STI) bias approach presented by Johnston [9] enables shock-tube radiation measurements to be mapped along the streamlines of a hypersonic flowfield solution based on the Lagrangian time from the shock (t_{shock}) and the normal shock velocity ($V_{N,shock}$). This approach assumes either the streamline is essentially at a constant pressure, or that the dominant emission occurs near the shock, meaning the dominant emission occurs prior to pressure gradients along the streamline. These assumptions allow the post-shock emission profiles obtained in a shock tube, which are at essentially a constant post-shock pressure, to be mapped to the vehicle flowfield. This approach is especially useful for assessing Titan [17] and Mars [18] entry backshell radiation, where the dominant emission occurs near the shock, and the separated wake flow region is not emitting or absorbing. These characteristics allow the STI bias approach to be applied to inform the backshell radiative heating margins or uncertainty for Titan and Mars entry cases. To enable the STI bias approach to be applied, however, the shock tube measurements at free-stream velocities that match $V_{N,shock}$ for the backshell streamlines must be obtained.

The flowfield property binning approach developed in this work allows the appropriate free-stream velocities for the STI bias analysis to be precisely determined for a given flight condition and surface point on the backshell. To enable this assessment, the flowfield property binning is performed using t_{shock} and $V_{N,shock}$ as the binning variables, instead of temperature and pressure. Section II.C showed that matching pressure-temperature bins between two flowfield cases meant that the two cases were exactly the same radiation problems, assuming optically-thin radiation and thermochemical equilibrium. For t_{shock} - $V_{N,shock}$ bins, the same conclusion is reached by making the optically-thin and constant pressure assumption, which means the thermochemical equilibrium assumption is no longer required. These assumptions make E in Eq. (8) a function of only t_{shock} and $V_{N,shock}$, which allows for the analogous simplification to Eq. (9). As discussed with the pressure-temperature binning in Section II.C, the flowfield property binning approach remains useful when these assumptions are not satisfied.

To demonstrate the use of flowfield property binning for targeting shock tube conditions to inform specific non-stagnation point environments, a Titan entry at a free stream velocity of 5.6 km/s, density of 6×10^{-4} kg/m³, and temperature of 160 K is considered. The geometry is the same scaled Genesis capsule considered by Johnston et al. [17]. The free-stream mass fractions are set to 0.9873 for N₂ and 0.0127 for CH₄, which results in a free-stream gas constant R of 299.55 J/kg. This gas constant is convenient for converting the flight pressures to shock-tube conditions, while maintaining the free-stream density. This conversion is required because the free-stream temperature is larger for the shock-tube conditions. This conversion is $p_{ST} = \rho_{flight} R T_{ST}$, where $T_{ST} = 300$ K, where the subscript ST indicates shock-tube conditions.

The flowfield simulations are performed using the LAURA/HARA code using the models discussed by Johnston et al. [17]. As a post-processing step to the flowfield simulations, the FPB approach is applied using t_{shock} - $V_{N,shock}$ bins for the CN Red dominated 600 - 1200 nm wavelength range. This spectral range provides the dominant contribution to the backshell radiative heating for Titan entry. For reference, the $V_{N,shock}$ flowfield distribution for this case is presented in Fig. 16. Note that, as discussed by Johnston [9], these $V_{N,shock}$ values are obtained by following each point in the

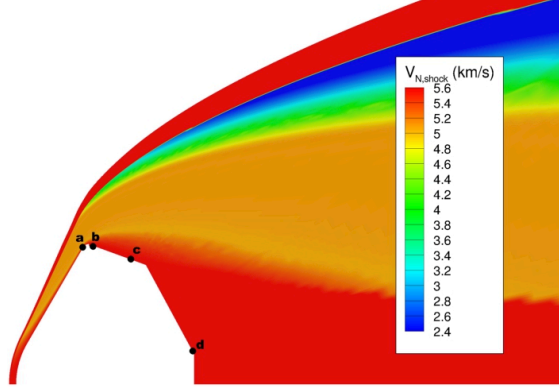


Fig. 16 Flowfield distribution of the streamline normal shock velocity for the Titan entry case.

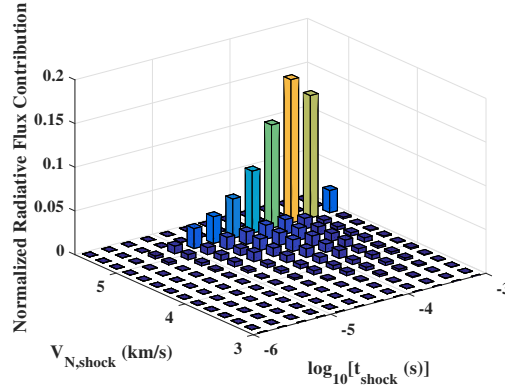


Fig. 17 Radiative heating bin distributions for surface point (a) for the Titan entry case.

flowfield back along the streamline until the shock is reached, at which point $V_{N,shock}$ is evaluated based on the angle of the shock relative to the free-stream velocity. Also shown in this figure are the backshell surface points considered in this analysis.

When targeting shock-tube conditions using t_{shock} - $V_{N,shock}$ binning, the t_{shock} binning is required to show that the dominant emission occurs within the available test time in the shock tube measurement. For Titan entry conditions, this test time extends to roughly $\log_{10}[t_{shock}(s)] = -3.2$. For the present cases, this restriction is satisfied for most conditions, and if it is not, then binary scaling of a higher pressure case can extend this time [9]. Therefore, the emphasis of the present analysis will be on $V_{N,shock}$. An example of the t_{shock} - $V_{N,shock}$ bin distribution is presented in Fig. 17 for surface point (a). Only the last row of the $\log_{10}[t_{shock}(s)]$ axis is beyond the above test limit, which is seen to provide less than 3% to the radiative flux to this point.

By summing the bin contributions in the t_{shock} dimension, the t_{shock} - $V_{N,shock}$ bin distribution is reduced to a function of $V_{N,shock}$ only. These distributions are presented in Fig. 18 for the four surface locations considered. The 10% Lower Bound limit shown in these figures omits 10% of the radiative flux at lower velocities. This bound is chosen to represent the lower limit of the $V_{N,shock}$ values of interest for this case. Similarly, the upper bound is chosen so that 10% of the radiative flux is omitted at higher velocities. For many cases, however, the upper limit cannot omit this 10% because of the highly populated upper bins. In this case, the upper limit captures the upper value of $V_{N,shock}$ with a noticeable bin population (this is seen for all surface points in Fig. 18, except for (d)). These upper and lower bounds on $V_{N,shock}$ represent the recommended bounds for the shock-tube velocities, which is the goal of this analysis. Note that these bounds avoid the tails of the bin distributions to focus the recommended velocities on the most impactful values.

Figure 18 shows that as the surface point moves from the forebody (a) toward the back of the vehicle (d), the bin peak is redistributed toward the lower $V_{N,shock}$ values. The cause of this redistribution is due to the aft points seeing more of the weaker oblique shock above the shoulder, as shown in Fig. 16. The nonzero bin value in Fig. 18(d) near 5600 m/s, which is the free-stream velocity, is due to the separated wake flow contribution. This separated flow region originates in

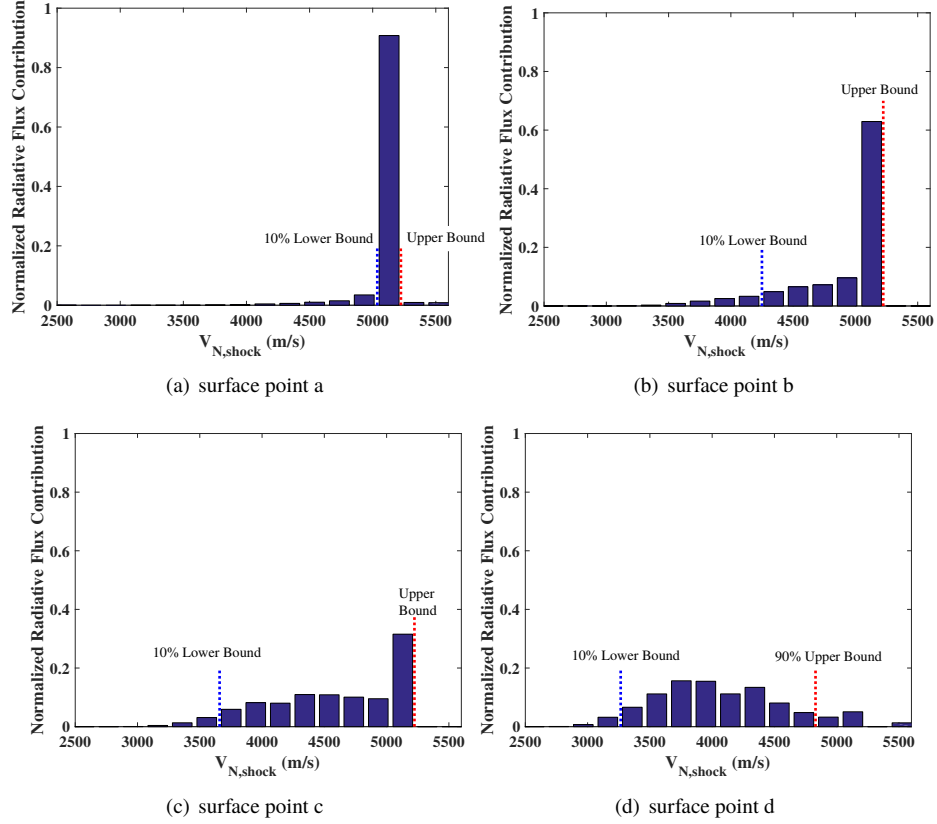


Fig. 18 Radiative heating bin distributions for each surface point for the Titan entry case.

the stagnation region, and therefore has near free-stream values for $V_{N,shock}$. Typically, this region provides a negligible contribution to the radiative flux due to its low pressure and number density. This contribution is small for this case, but it is mentioned here because its small contribution is seen in the bin distribution for surface point (d).

VI. Conclusions

The flowfield property binning (FPB) approach is developed to provide a quantitative method for establishing similarity between shock-layer radiation problems. If one of these cases represents a measurement, then this similarity analysis determines the relevance of the measurement to the other case. This measurement could include surface normal intensity, observed radiation, or shock tube profile measurements. The FPB approach reduces the simulation of these measurements into a set of bins based on local temperature and pressure or t_{shock} and $V_{N,shock}$. For matching pressure-temperature bins between two cases, the dependence of the simulation on the radiation model evaluated at a set of pressures and temperatures is exactly the same. Therefore, experimental validation for one of these cases is considered relevant to the other case with matching bins. The histogram intersection algorithm is proposed to provide a quantitative metric of agreement between the bin distributions, resulting in the histogram intersection factor H . The closer H is to 1.0, the better the two bin distributions compare. This value of H may be used to weight the impact of the experimental validation case to the radiative heating uncertainty or margin of the flight or design case. A benefit of this FPB framework is that it allows observed radiation measurements, which represent a geometrically different radiation problem, to be directly applied to radiative heating margin assessments. Even for H factors as low as 0.3 between an observed radiation measurement and the radiative heating to flight vehicle, the experimental validation provided by the observed radiation measurement is valuable due to the rarity of flight radiation measurements. This increases the value of these observed radiation measurements, which provides further motivation for obtaining future measurements. The FPB approach is also shown to allow shock-tube measurements to target velocities relevant to backshell radiative

heating for Titan and Mars entry. These shock-tube measurements may then be used in the shock-tube informed bias approach to directly inform the backshell radiative heating uncertainty or margin.

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