Thermochemical effects on hypersonic shock waves interacting with weak turbulence

Charlas El Almendro 2021

Alberto Cuadra [1, a] , César Huete[1], Marcos Vera[1], & Javier Urzay[2]

[a] acuadra@ing.uc3m.es

[1] Grupo de Mecánica de Fluidos, Universidad Carlos III de Madrid
[2] Center for Turbulence Research, Stanford University

Málaga | December 22, 2021

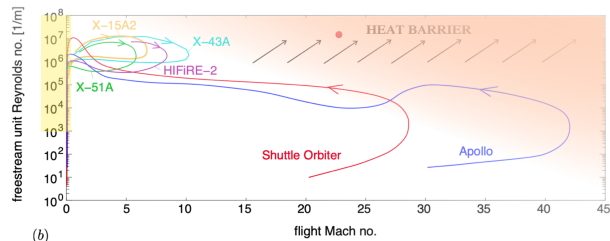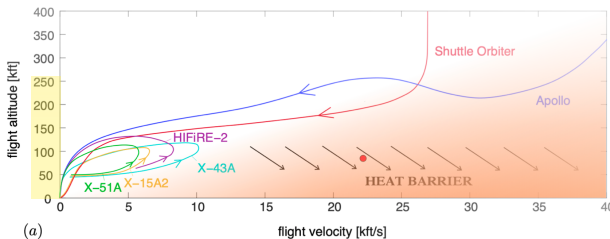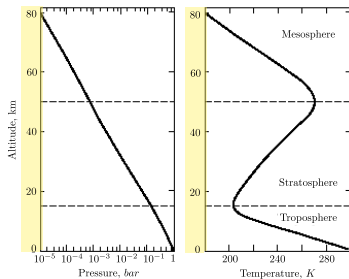UNIVERSIDAD DE MÁLAGA   uc3m | Universidad Carlos III de Madrid   CTR | Stanford University CENTER FOR TURBULENCE RESEARCH

Motivation

uc3m

Thermochemical
effects on hypersonic
shock waves
interacting with weak
turbulence

A. Cuadra (presenter)
C. Huete, M. Vera,
J. Urzay

1. Motivation

Effects of dissociation
and vibrational
excitation on the mean
post-shock quantities

LIA of turbulence
interacting with
hypersonic shocks

Extension for real air
mixture

Conclusion

$$\frac{\Delta p}{p} \sim \frac{\Delta \rho}{\rho} = O(10^5), \qquad \frac{\Delta T}{T} = O(1).$$

In hypersonic flight near the ground, the Reynolds number becomes large because of the comparatively larger densities

$$\frac{\Delta Re}{Re} = O(10^5).$$

Urzay, J., & Di Renzo, M. (2021). Annual Research Briefs, Center for Turbulence Research, 7-32.

UNIVERSIDAD DE MÁLAGA

Motivation

uc3m

Thermochemical
effects on hypersonic
shock waves
interacting with weak
turbulence

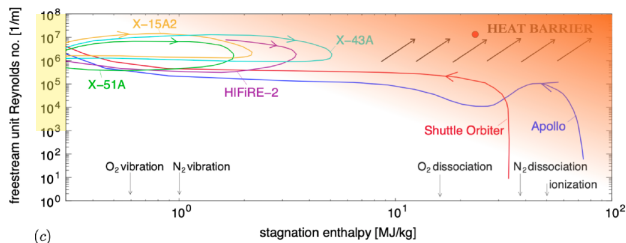A. Cuadra (presenter)
C. Huete, M. Vera,
J. Urzay

2 Motivation

Effects of dissociation
and vibrational
excitation on the mean
post-shock quantities

LIA of turbulence
interacting with
hypersonic shocks

Extension for real air
mixture

Conclusion

UNIVERSIDAD DE MÁLAGA

Urzay, J., & Di Renzo, M. (2021). Annual Research Briefs, Center for Turbulence Research, 7-32.

Hypersonic flight at low altitudes is characterized by:

- High free-stream Mach numbers $Ma \geq 5$
- High free-stream and post-shock
  unit Reynolds numbers $Re \sim 10^7 - 10^9$ m^{-1}
- High stagnation enthalpies $h_0 \sim 5 - 30$ MJ/kg

- Small mean free paths $\lambda \sim 0.1\ \mu$m

- large normal Mach numbers
- turbulent boundary layers

- much higher than the vibrational specific energies
  of O$_2$ and N$_2$

- short vibrational relaxation distances

Effects of dissociation and vibrational excitation on the mean post-shock quantities

uc3m

Thermochemical effects on hypersonic shock waves interacting with weak turbulence

A. Cuadra (presenter) C. Huete, M. Vera, J. Urzay

Motivation

3 Effects of dissociation and vibrational excitation on the mean post-shock quantities

LIA of turbulence interacting with hypersonic shocks

Extension for real air mixture

Conclusion

Integral conservation equations accross shock waves in dissociating gases

$$\rho_1 u_1 = \rho_2 u_2,$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2,$$

$$e_1 + p_1/\rho_1 + u_1^2/2 = e_2 + p_2/\rho_2 + u_2^2/2 + q_d,$$

Upstream flow is sufficiently cold to be approximated as

$$e_1 = (5/2)R_{g,A_2}T_1, \quad p_1 = \rho_1 R_{g,A_2}T_1.$$

Effects of dissociation and vibrational excitation on the mean post-shock quantities

uc3m

Thermochemical effects on hypersonic shock waves interacting with weak turbulence

A. Cuadra (presenter)
C. Huete, M. Vera,
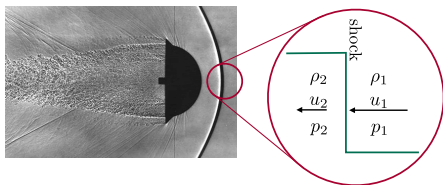J. Urzay

Motivation

3 Effects of dissociation and vibrational excitation on the mean post-shock quantities

LIA of turbulence interacting with hypersonic shocks

Extension for real air mixture

Conclusion

Integral conservation equations accross shock waves in dissociating gases
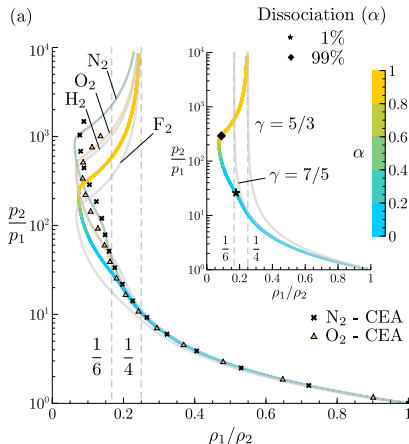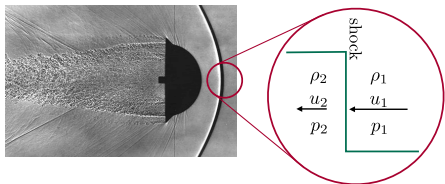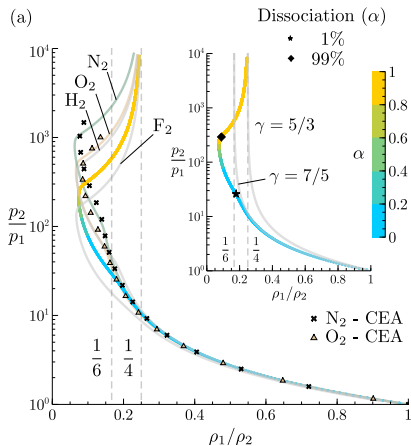
$$\rho_1 u_1 = \rho_2 u_2,$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2,$$

$$e_1 + p_1/\rho_1 + u_1^2/2 = e_2 + p_2/\rho_2 + u_2^2/2 + q_d,$$

$$p_2 = \rho_2 R_{g,\mathrm{A_2}} T_2 (1+\alpha), \quad q_d = \alpha R_{g,\mathrm{A_2}} \Theta_d,$$

$$e_2 = R_{g,\mathrm{A_2}} T_2 \left[3\alpha + (1-\alpha) \left(\frac{5}{2} + \frac{\Theta_v/T_2}{e^{\Theta_v/T_2} - 1} \right) \right],$$

$$\frac{\alpha^2}{1-\alpha} = Gm\Theta_r \left(\frac{\pi m k_B}{\hbar^2} \right)^{3/2} \frac{\sqrt{T_2}}{\rho_2} e^{-\frac{\Theta_d}{T_2}} \left(1 - e^{-\frac{\Theta_v}{T_2}} \right),$$

(a)

where α is the degree of dissociation, defined as the mass fraction of A atoms in the reaction $\mathrm{A_2} \rightleftharpoons \mathrm{A} + \mathrm{A}$, that must be solved with the aid of the chemical equilibrium condition.

UNIVERSIDAD DE MÁLAGA

Effects of dissociation and vibrational excitation on the mean post-shock quantities

uc3m

Thermochemical
effects on hypersonic
shock waves
interacting with weak
turbulence

A. Cuadra (presenter)
C. Huete, M. Vera,
J. Urzay

Motivation

4 Effects of dissociation
and vibrational
excitation on the mean
post-shock quantities

LIA of turbulence
interacting with
hypersonic shocks

Extension for real air
mixture

Conclusion

Jump conditions

Endothermicity due to dissociation and vibrational excitation does the following:

- increases the mean post-shock density
- decreases the mean post-shock velocity
- decreases the mean post-shock Mach number
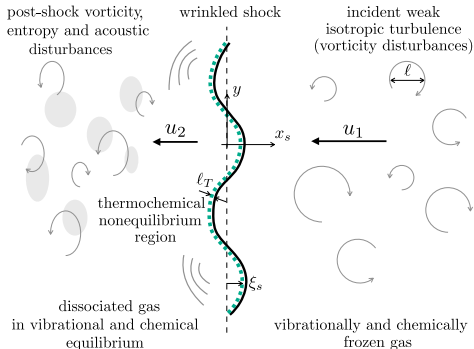- decreases the mean post-shock temperature

UNIVERSIDAD DE MÁLAGA

Considering:

- turbulence is comprised of small fluctuations,
- Kovasznay decomposition into vortical, entropic and acoustic modes,

we can solve this problem analytically by using

- linearized Rankine-Hugoniot relations,
- linearized Euler equations in the post-shock gas.

post-shock vorticity, entropy and acoustic disturbances

wrinkled shock

incident weak isotropic turbulence (vorticity disturbances)

u_2 u_1

y x_s

ℓ

ℓ_T

thermochemical nonequilibrium region

ξ_s

dissociated gas in vibrational and chemical equilibrium

vibrationally and chemically frozen gas

Limits of validity

Assumptions standard LIA:

(a) $\mathrm{rms}(u_\ell) \ll a_1$ and a_2,

(b) $\xi_s \ll \ell$,

(c) $\ell/u_\ell \ll \ell^2/\nu$.

With thermochemical effects:

(d) $\ell_T \ll \ell$

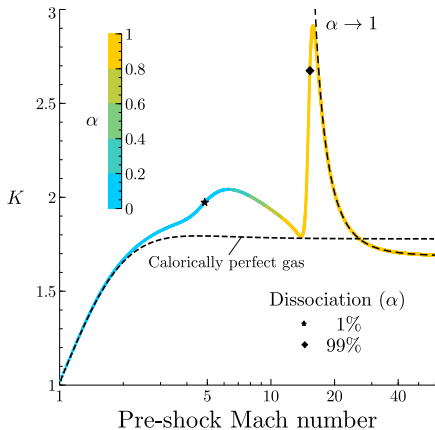For a given ℓ, this condition becomes increasingly more accurate as the altitude decreases.

UNIVERSIDAD DE MÁLAGA

uc3m

Thermochemical
effects on hypersonic
shock waves
interacting with weak
turbulence

A. Cuadra (presenter)
C. Huete, M. Vera,
J. Urzay

Motivation

Effects of dissociation
and vibrational
excitation on the mean
post-shock quantities

6 LIA of turbulence
interacting with
hypersonic shocks

Extension for real air
mixture

Conclusion

Turbulent Kinetic Energy

Turbulence intensity and Turbulent Reynolds number

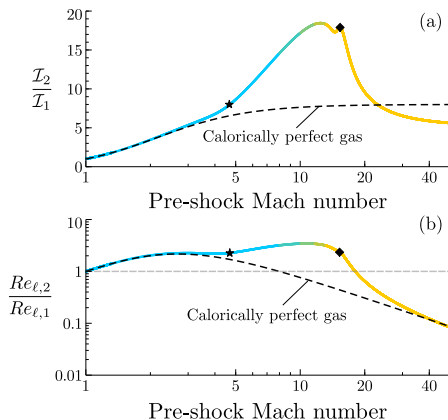For a calorically perfect gas:

$$K \sim 1.75$$

At hypervelocities $(Ma \gtrsim 10)$, the calorically perfect gas approximation predicts a saturation in the amplification of kinetic energy and turbulence intensity, along with a decrease in the turbulent Reynolds number accross the shock.
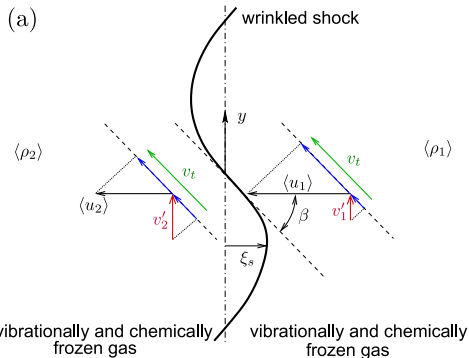
Turbulent Kinetic Energy
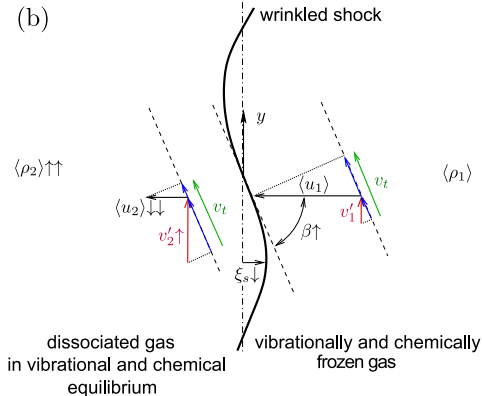
Turbulence intensity and Turbulent Reynolds number

In contrast, the incorporation of dissociation and vibrational excitation predicts larger kinetic energy and turbulence intensity amplification rates, along with an increase in the turbulent Reynolds number accross the shock.
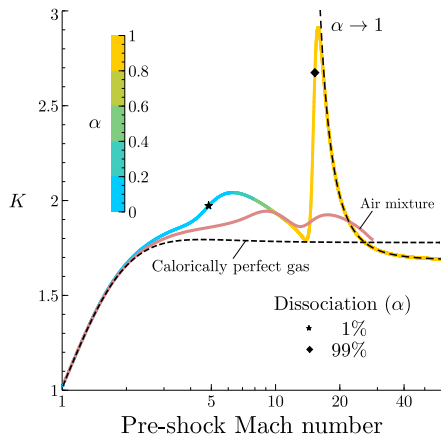
UNIVERSIDAD DE MÁLAGA

LIA mechanism of turbulence amplification across hypersonic shocks

uc3m

Thermochemical effects on hypersonic shock waves interacting with weak turbulence

A. Cuadra (presenter) C. Huete, M. Vera, J. Urzay

Motivation

Effects of dissociation and vibrational excitation on the mean post-shock quantities

8 LIA of turbulence interacting with hypersonic shocks

Extension for real air mixture

Conclusion

Calorically perfect gas

(a)

wrinkled shock

y

$\langle \rho_2 \rangle$ $\langle \rho_1 \rangle$

v_t v_t

$\langle u_2 \rangle$ $\langle u_1 \rangle$

v'_2 v'_1

β

ξ_s

vibrationally and chemically frozen gas   vibrationally and chemically frozen gas

Vibrationally Excited, Dissociating Gas

(b)

wrinkled shock

y

$\langle \rho_2 \rangle \uparrow\uparrow$ $\langle \rho_1 \rangle$

v_t v_t

$\langle u_2 \rangle \downarrow\downarrow$ $\langle u_1 \rangle$

$v'_2 \uparrow$ v'_1

$\beta \uparrow$

$\xi_s \downarrow$

dissociated gas in vibrational and chemical equilibrium   vibrationally and chemically frozen gas
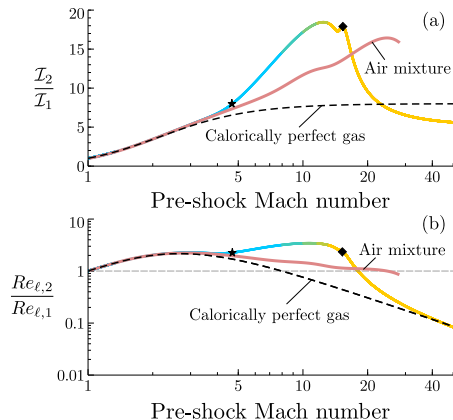
Conservation of tangential momentum dictates that the transverse velocity fluctuations should increase across the shock – these are larger at hypersonic velocities because of the associated larger post-shock densities induced by endothermic thermochemical effects.

UNIVERSIDAD DE MÁLAGA

uc3m

Thermochemical effects on hypersonic shock waves interacting with weak turbulence

A. Cuadra (presenter) C. Huete, M. Vera, J. Urzay

Motivation

Effects of dissociation and vibrational excitation on the mean post-shock quantities

LIA of turbulence interacting with hypersonic shocks

9 Extension for real air mixture

Conclusion

Get the code

Turbulent Kinetic Energy

Turbulence intensity and Turbulent Reynolds number

In case of a real air mixture (recombination in multi-species gas and electronic excitation) there is a significant decrease of the peaks values of TKE. However, the qualitative picture remains intact.

Key takeaways

- Significant departures from calorically perfect gas behaviour can be observed in the solution even at modest degrees of dissociation of 1%.

- The amplification of TKE doubles that observed in calorically perfect gases, with most of the content of TKE downstream in form of vortical modes.

- The turbulent Reynolds number is amplified across the shock at hypersonic Mach numbers in the presence of dissociation and vibrational excitation, as opposed to the attenuation observed in the calorically perfect case.

- Preliminary results show that real air mixture share qualitative results, but with lower amplitudes.

- **Thermochemical effects arising at hypersonic velocities appear to enhance turbulent fluctuations in the post-shock gas.**

Huete, C. et al. (2021). Thermochemical effects on hypersonic shock waves interacting with weak turbulence. Physics of Fluids, 33(8), 086111

UNIVERSIDAD DE MÁLAGA

uc3m Universidad Carlos III de Madrid

CTR | Stanford University CENTER FOR TURBULENCE RESEARCH