항공우주 공력:
모델링-CFD, 난제-린치핀, 그리고 전망

Aerodynamics for Aerospace: Modeling-CFD, Challenge-Linchpin, and Outlook

명 노 신

경상국립대학교 우주항공대학 교수(1999-현재)

Aerospace Computational Modeling Laboratory (ACML)

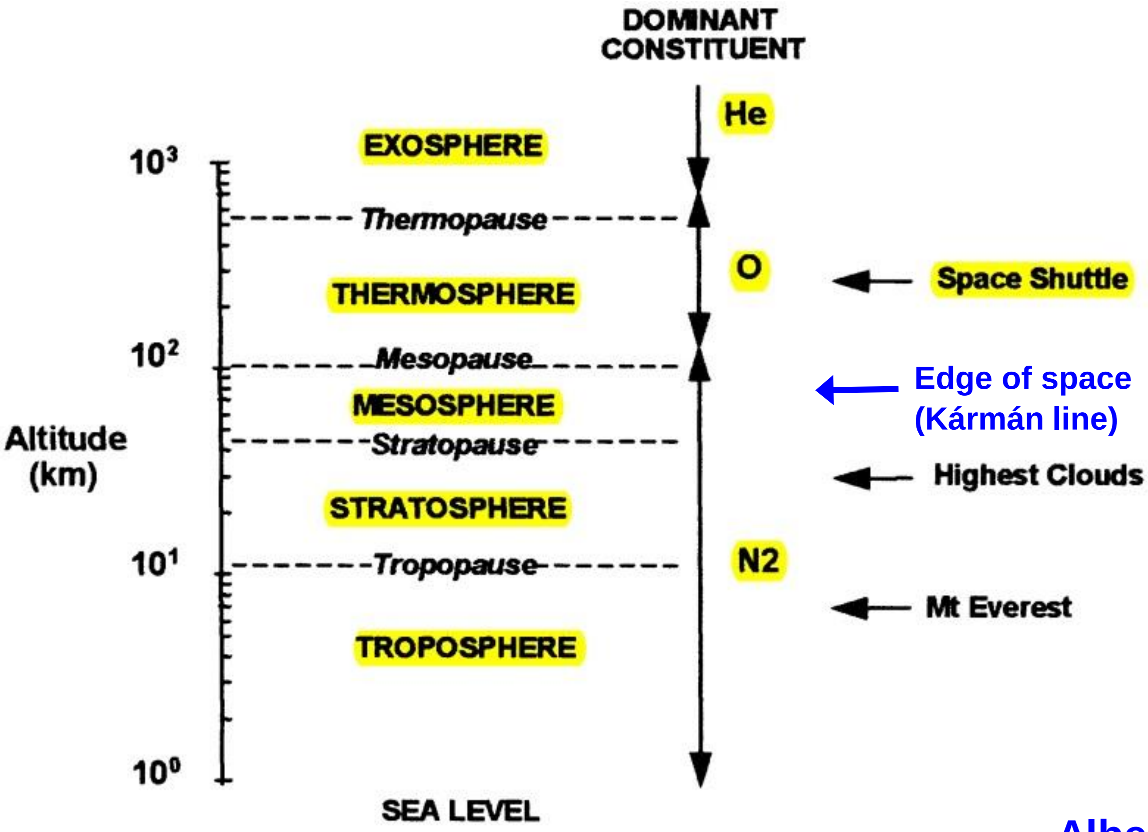
http://acml.gnu.ac.kr/

글로벌 항공핵심기술 선도연구센터(ERC; 과기정통부), 센터장(2017-현재)
수소연료전지 커뮤터기 지역혁신메가프로젝트(RIMP; 과기정통부), 사업단장(2023-현재)

2024년 한국항공우주학회 공기역학 워크숍, 대전 호텔 ICC, 7월 12일 (금) 09:00 – 09:40

항공우주 공력 정의

Definition of air (aero): the mixture of gases that surrounds the earth (& planet)



Edge of space (Kármán line)

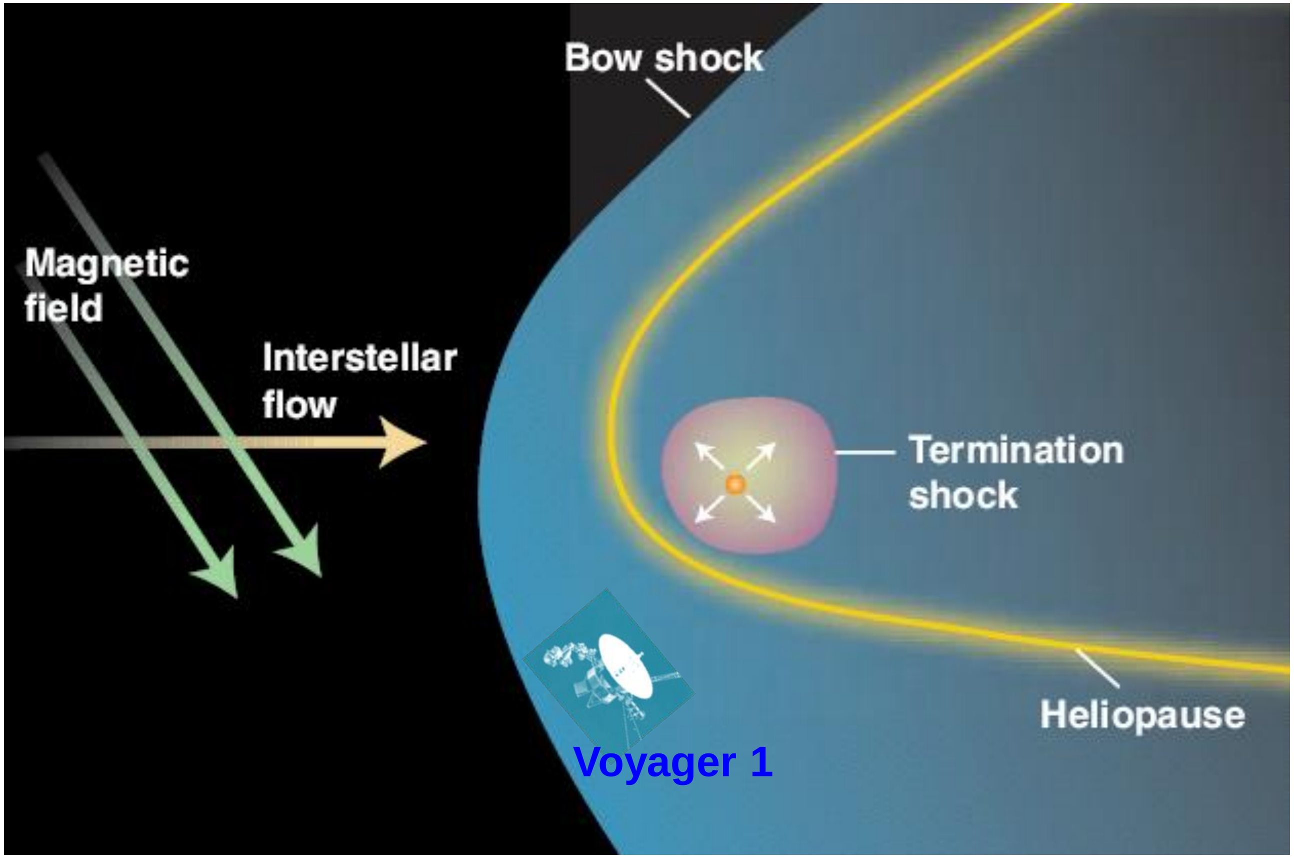
SpaceX loses dozens of new Starlink satellites to "geomagnetic storm"

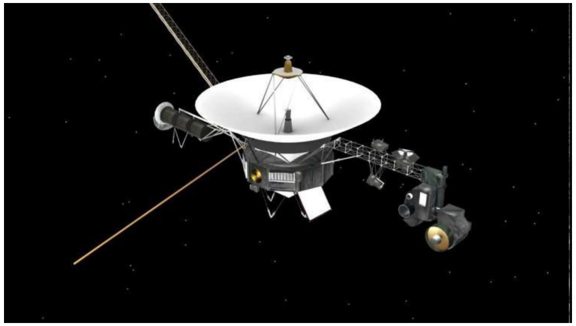
Albert F. Zahm (US)

"Superaerodynamics," Journal of the Franklin Institute, Vol. 217, pp. 153-166, 1934.

Space: solar system

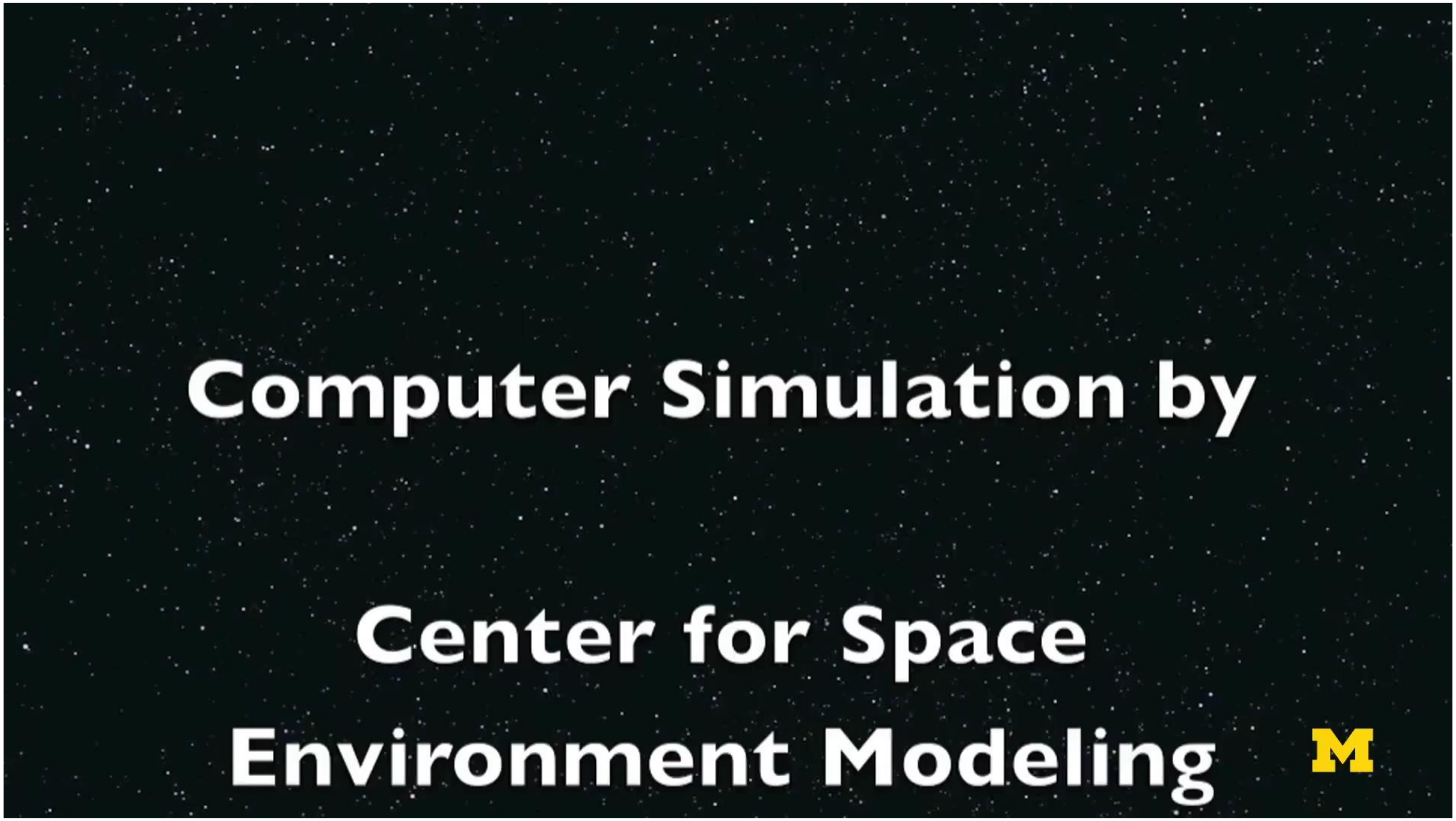
Interstellar shock waves: “*An understanding of interstellar shock waves is crucial in determining the structure of the interstellar medium. It is a tenuous plasma filling the galactic disk that has a mean density of only about one particle per cubic centimeter*” (McKee & Draine, *Science*, 1991).





Voyager 1 (1977)

Modeling & Simulation of Space Environment



Computer Simulation by

Center for Space Environment Modeling

우주항공 강국 발전을 위한 원리와 전략

국방(Defense) ⟸ ⟹ 민수(Civil)

안보(S)·국방 마중물

안보·국방 임무로 출발

이후 대규모 민수시장 창출 (예, GPS, 위성통신, ???)

국민적 관심

장기적 로드맵

Security

임무중심(M) 전후방효과

과학기술과 산업 전후방효과가 큰 분야 우선

근원적 질문 천착 필요(예, Why 재사용?)

Story 있는 임무·사업 (The Moon vs Dune)

임무의 중요성, 세부기술의 융합, 항공기술 접목 (예, 우주비행기)

Mission

개척·혁신(I) 플랫폼 플래그십

주력화 달성에 혁신 Spirit과 조직이 핵심요소 (예, 미국, 프랑스, 이스라엘)

플랫폼(기반·파생 충족, 파편화 해소)

규모, 경쟁, 적정 이익 보장을 통해 신규시장 창출과 한계극복

Disruptive 기업, 스타트업, Venture Capital

Innovation

전략적모델 비교우위(C)

비교우위(시장, 기술·인증, 후속 지원)와 리스크 관리

순수국내, 국외법인, 국제공동 개발 모델

국내기업 우수 기술(ICT, 배터리, 수소, 항공기 체계, 원자력, 방산)과 지역(인접산업 연계, 인프라) 비교우위 적극 활용

Comparative Advantage

생산성(P) 인재양성

$K \cdot C^{\alpha} \cdot L^{\beta}$

총요소생산성(K) (미국의 61%)

글로벌 대비 부족 항목 (혁신성, 규제환경, 사회적자본) 개선

지역 비교우위 적극 활용

인적자원 역량(β) 강화

Productivity

사례: 비교우위 전략 (M-I-C-P)

중국 우주비행기 및 극초음속 비행체 개발 굴기(2023)

중국 극초음속 비행체

로봇 우주비행기 9개월 궤도 임무 후 착륙(2023년 5월 8일)

초대형 풍동 CAS JF-22 (10 km/sec) 북경 인근에 구축(2023년 6월)

"China's JF-22 hypersonic wind tunnel blows by US" (ASIA Times, 2023년 6월 7일)

미국의 흥미로운 대응

> *"Due to a lack of hypersonic wind tunnels, the US Department of Defense's Defense Innovation Unit has reportedly considered skipping wind tunnel tests and instead getting data directly from actual flight testing."*

한국 적용 시사성

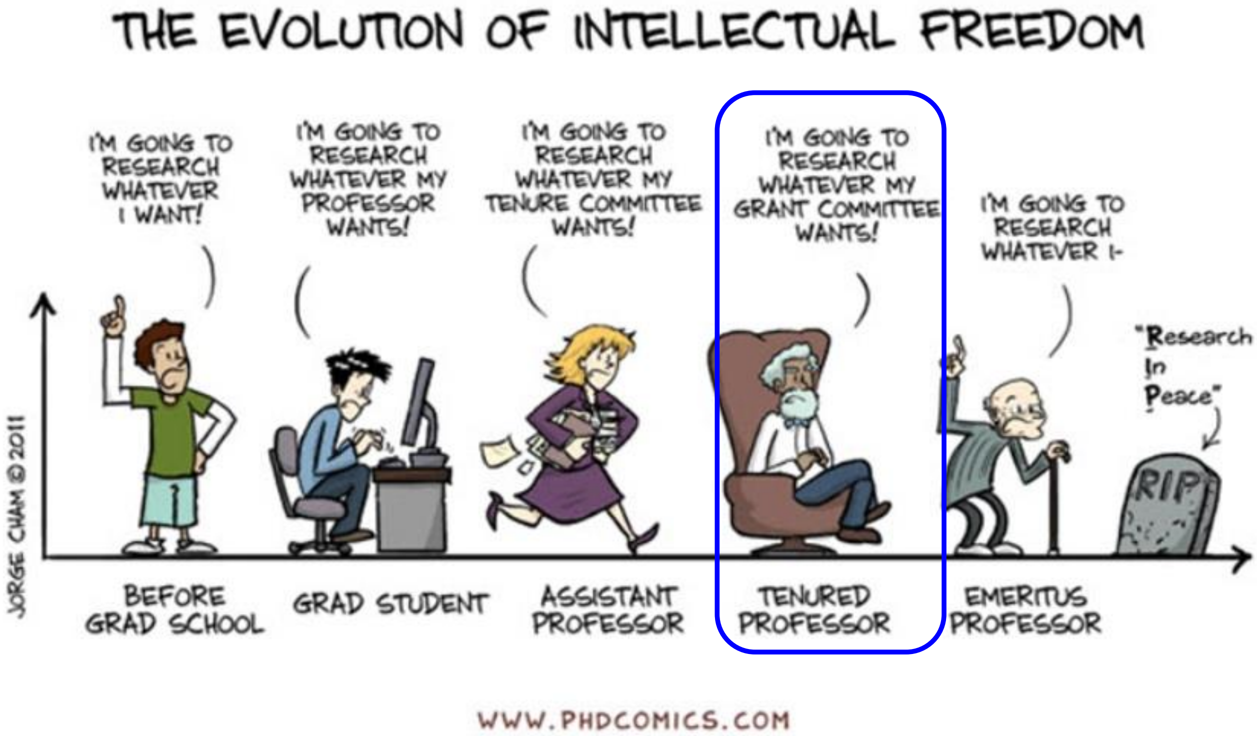
3축 체계(CFD-Wind Tunnel-Flight Test) 대신

2축 체계(CFD-Flight Test)

(Wind Tunnel은 시편 단위의 CFD* 검증용으로 주로 사용)

*CFD (Computational Fluid Dynamics; 전산유체역학)

연구주제 선택 배경 및 전략

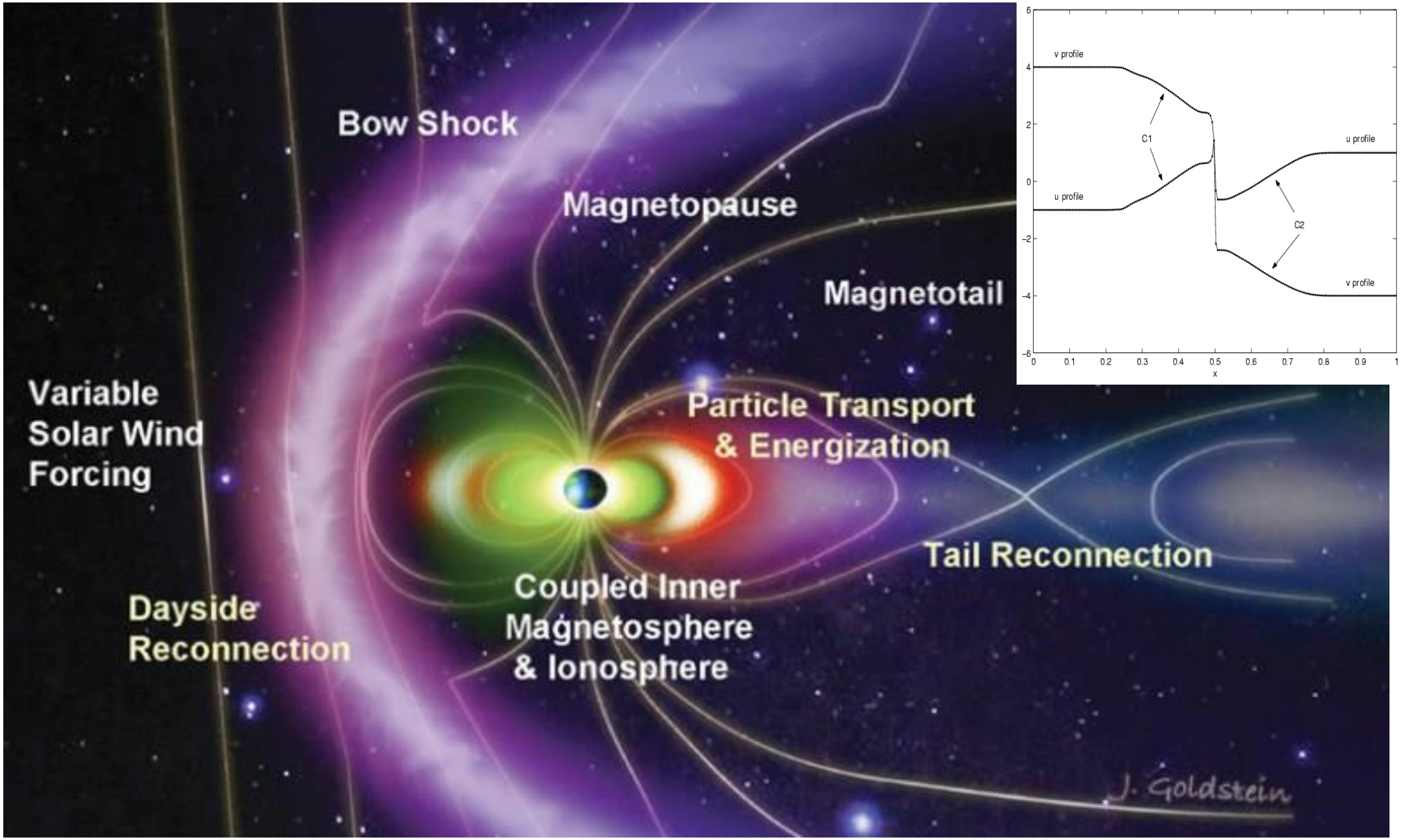


- 시대적 Issue
- Connecting the Dots
- Mission(시스템) 중심 및 융합
- 난제(Challenge)
- 린치핀(Linchpin)

- 개인연구: 기초연구
- 집단연구: 원천기술, 기술이전·사업화(기업 컨소시엄 또는 공동기관)
- 미래 KASA 사업: 대학-연구소-수요기업 추진체계?

MHD 기반 우주환경 모델링 난제 1

*MHD (Magnetohydrodynamics; 자기유체역학)



Two Compound Waves

MHD 기반 우주환경 모델링 난제 2

$$\begin{pmatrix}\rho\\ \rho\mathbf{u}\\ \mathbf{B}_\perp\\ E\end{pmatrix}_t + \begin{pmatrix}\rho u\\ \rho\mathbf{u}u+(p+\mathbf{B}_\perp\cdot\mathbf{B}_\perp/2)\mathbf{I}-B_x\mathbf{B}_\perp\\ u\mathbf{B}_\perp - B_x\mathbf{v}\\ (E+p+\mathbf{B}_\perp\cdot\mathbf{B}_\perp/2)u - B_x(\mathbf{B}_\perp\cdot\mathbf{v})\end{pmatrix}_x = \begin{pmatrix}0\\ D_1\mathbf{u}\\ D_2\mathbf{B}_\perp\\ \Sigma+\kappa T\end{pmatrix}_{xx}$$

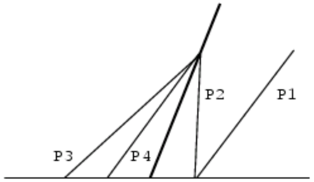
$$-c_f, -c_A, -c_s, 0, c_s, c_A, c_f;\quad c_s\le c_A\le c_f$$

$$c_A = |B_x|/\sqrt{\rho},\ 2c_{f,s}^2 = a^2+\frac{\mathbf{B}\cdot\mathbf{B}}{\rho}\pm\sqrt{\left(a^2+\frac{\mathbf{B}\cdot\mathbf{B}}{\rho}\right)^2-4a^2c_A^2},\ a^2=\frac{\gamma p}{\rho}$$

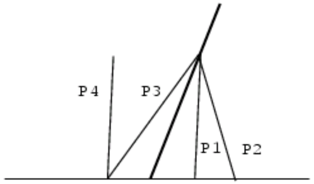
Non-strictly hyperbolic due to degeneracy

Triple umbilic point ($\mathbf{B}_\perp\cdot\mathbf{B}_\perp=0$ and $c_A=a$)

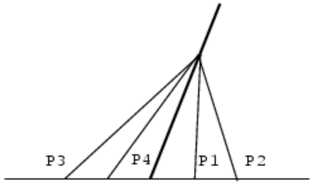
$c_s=c_A=\ c_f\ =a$



S1



S2



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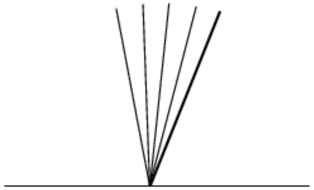
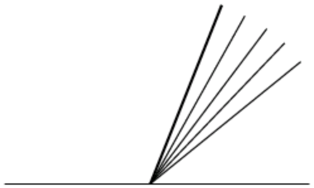
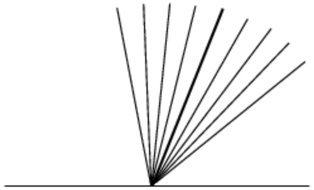


C1



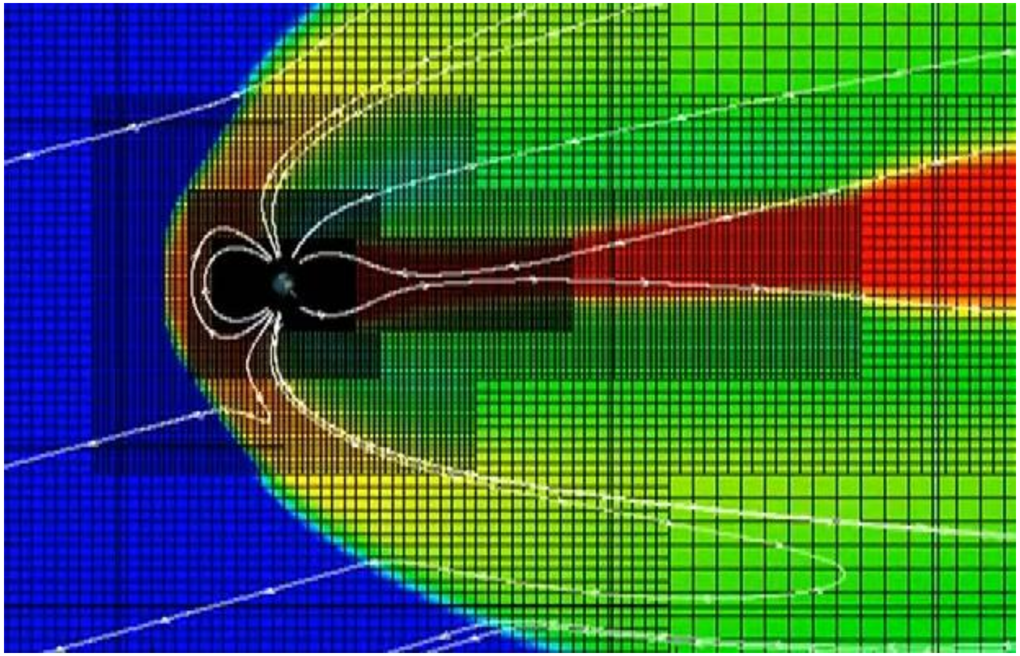
C2



C1C2

Viscosity admissibility condition on the global phase portrait of the dynamical system of shock structure

MHD 기반 우주환경 모델링 난제 3



16 level solution-adaptive Cartesian grid system for multi-scale flows

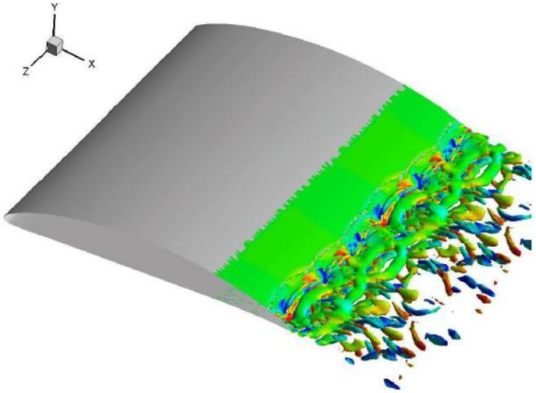
$$\begin{pmatrix} \rho \\ \rho\mathbf{u} \\ \mathbf{B} \\ E \end{pmatrix}_t + \nabla\cdot\begin{pmatrix} \rho\mathbf{u} \\ \rho\mathbf{uu}+(p+\mathbf{B}\cdot\mathbf{B}/2)\mathbf{I}-\mathbf{BB} \\ \mathbf{uB}-\mathbf{Bu} \\ (E+p+\mathbf{B}\cdot\mathbf{B}/2)\mathbf{u}-\mathbf{B}(\mathbf{B}\cdot\mathbf{u}) \end{pmatrix} = -\begin{pmatrix} 0 \\ \mathbf{B} \\ \mathbf{u} \\ \mathbf{B}\cdot\mathbf{u} \end{pmatrix}(\nabla\cdot\mathbf{B})$$

The div B = 0 condition can not be satisfied locally in one-dimensional framework and so we must **retain div B terms** in fully three-dimensional flow.

희박 및 극초음속 유동 난제 1

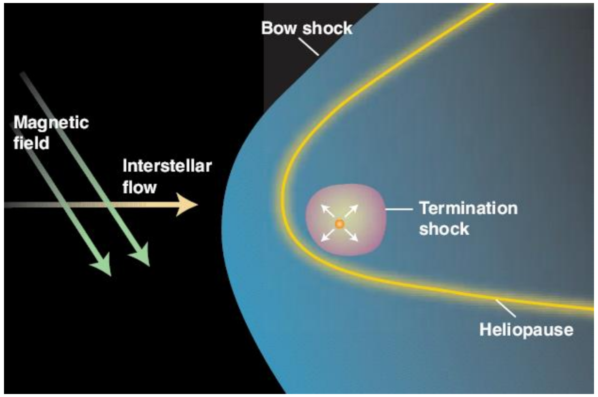
Two extremes

(High Reynolds chaotic) fluid dynamics is difficult because:



*At extremely small scales, even turbulent flow is very simple. It is smooth and well behaved. At larger scales, however, a fluid is subject to very few constraints. It can develop arbitrary levels of **complexity** like the effect of turbulence on separation*. (P. L. Roe, “Future developments in CFD,” ICAAT-GNU, May 2014)

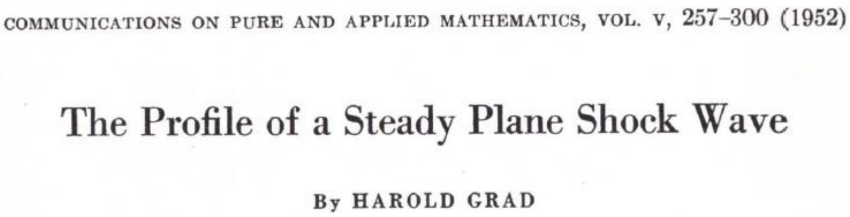
(Low Reynolds mesoscopic) fluid dynamics is difficult because:



*It involves **microscopic** collisional interactions among fluid particles and their **interplay** with the kinematic motion of particles in the macroscopic framework. This challenge is vividly illustrated by the **high Mach number shock singularity problem** (HMNP)*. (R. S. Myong, Physics of Fluids 2014)

⇨ **Rarefied & microscale gases**
And other complex systems

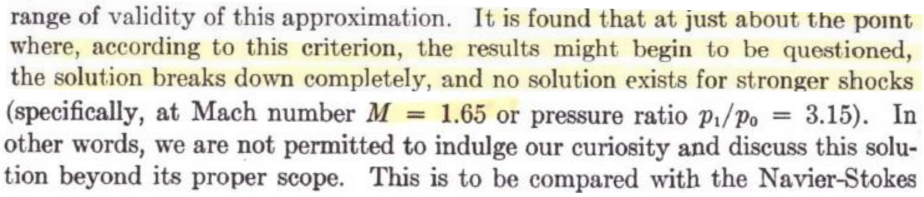
희박 및 극초음속 유동 난제 2



COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. V, 257–300 (1952)

The Profile of a Steady Plane Shock Wave

By HAROLD GRAD



range of validity of this approximation. It is found that at just about the point where, according to this criterion, the results might begin to be questioned, the solution breaks down completely, and no solution exists for stronger shocks (specifically, at Mach number $M = 1.65$ or pressure ratio $p_1/p_0 = 3.15$). In other words, we are not permitted to indulge our curiosity and discuss this solution beyond its proper scope. This is to be compared with the Navier-Stokes

Conservation laws (exact consequence of BKE)

$$\frac{\partial(\rho\mathbf{u})}{\partial t}+\nabla\cdot\left(\rho\mathbf{uu}+p\mathbf{I}+\boldsymbol{\Pi}\right)=\mathbf{0}$$

in conjunction with the constitutive relations (CR)

$$\frac{D}{Dt}(\boldsymbol{\Pi}/\rho)+\boxed{\nabla\cdot\Psi^{(\Pi)}}+2[\boldsymbol{\Pi}\cdot\nabla\mathbf{u}]^{(2)}+2p[\nabla\mathbf{u}]^{(2)}=\boxed{\left\langle m[\mathbf{cc}]^{(2)}C[f,f_2]\right\rangle\left(\equiv\boldsymbol{\Lambda}^{(\Pi)}\right)}$$

2nd-order closure

2nd-order closure

$$\underset{2nd}{=}-\frac{p}{\mu_{NS}}\boldsymbol{\Pi}q_{2nd}(\kappa_1)\text{ where }\Psi^{(\Pi)}=\langle m\mathbf{ccc}f\rangle-\langle m\mathrm{Tr}(\mathbf{ccc})f\rangle\mathbf{I}/3$$

$$q_{2nd}(\kappa_1)\equiv\frac{\sinh\kappa_1}{\kappa_1},\quad\kappa_1\equiv\frac{T^{1/4}}{p}\left(\frac{\boldsymbol{\Pi}:\boldsymbol{\Pi}}{\mu_{NS}}+\frac{\mathbf{Q}\cdot\mathbf{Q}/T}{k_{NS}}\right)^{1/2}$$

Onsager-Rayleigh dissipation function

Distribution function in the exponential form

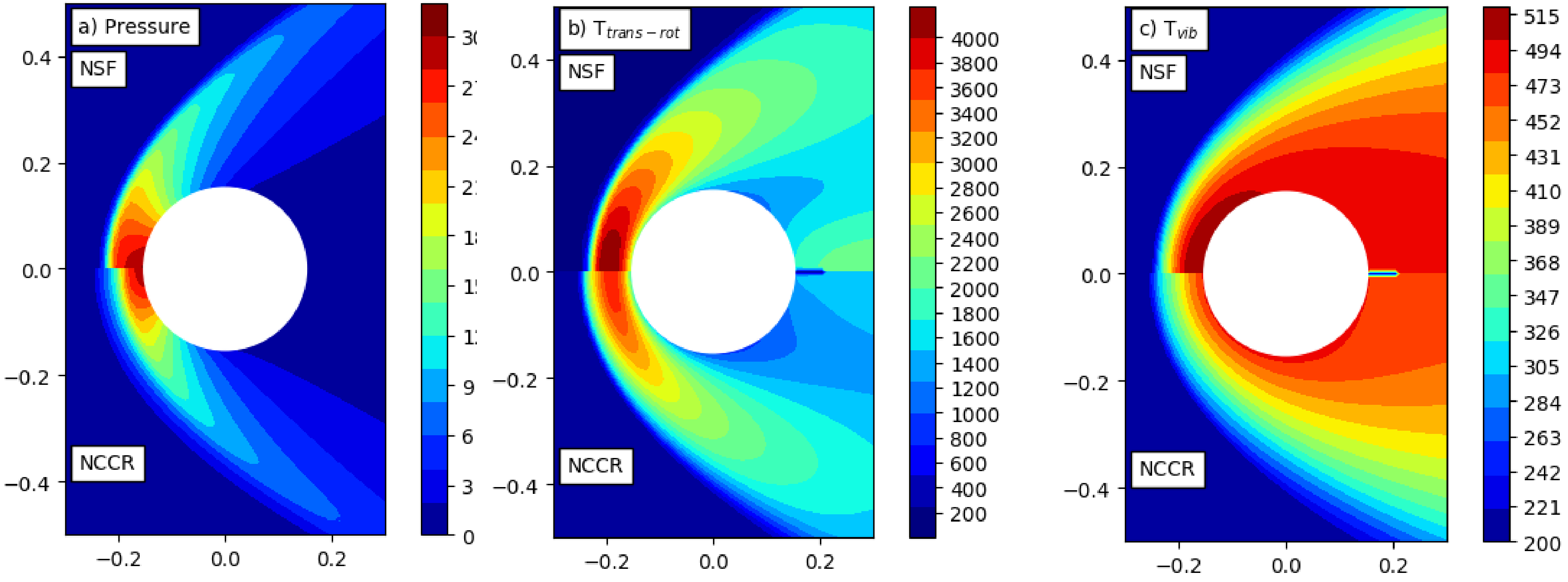
$$f=\exp\left[-\beta\left(\frac{1}{2}mc^2+\sum_{n=1}^{\infty}X^{(n)}h^{(n)}-N\right)\right],\ \beta\equiv\frac{1}{k_BT}$$

Cumulant expansion

$$\left\langle e^{\lambda x}\right\rangle=\sum_{l=0}^{\infty}\frac{\lambda^l}{l!}\left\langle x^l\right\rangle=\exp\left[\sum_{l=1}^{\infty}\frac{\lambda^l}{l!}\kappa_l\right]$$

희박 및 극초음속 유동 난제 3

nccrVibFOAM solver was developed as an extension to the *dbnsTurbFoam* solver by implementing additional algebraic constitutive relations for the stress tensor and heat flux vector (*Comp. Phys. Comm*. 2024)



Mach 10 nitrogen gas (Kn=0.05)

희박 및 극초음속 유동 난제 4

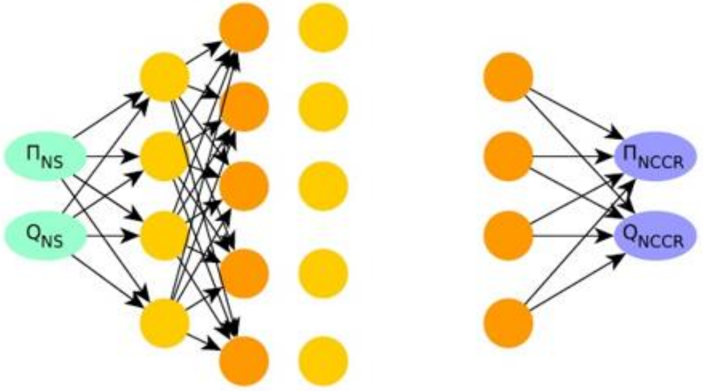
Physics-guided: CR derived theoretically from Boltzmann kinetic equation (kinematic & collision physics)

Ultra-fast DSMC based on explainable AI for all flow regimes including rarefied hypersonics

FVM-CL and CR-DSMC ~ Same order of computing time as FVM-NS

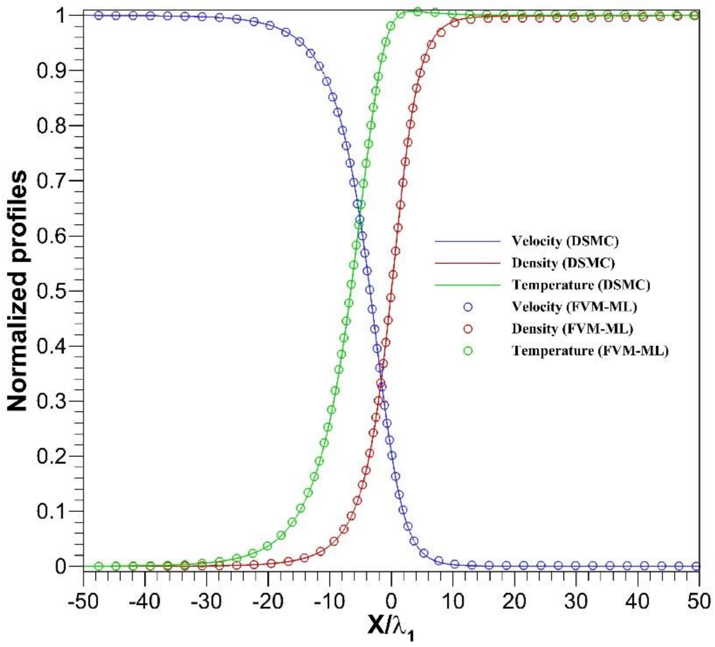
NS CR can be incorporated into CR of the ML-DSMC near thermal equilibrium.

Multi-dimensional flows via decomposition



DNN model

FVM-DSMC-ML solver



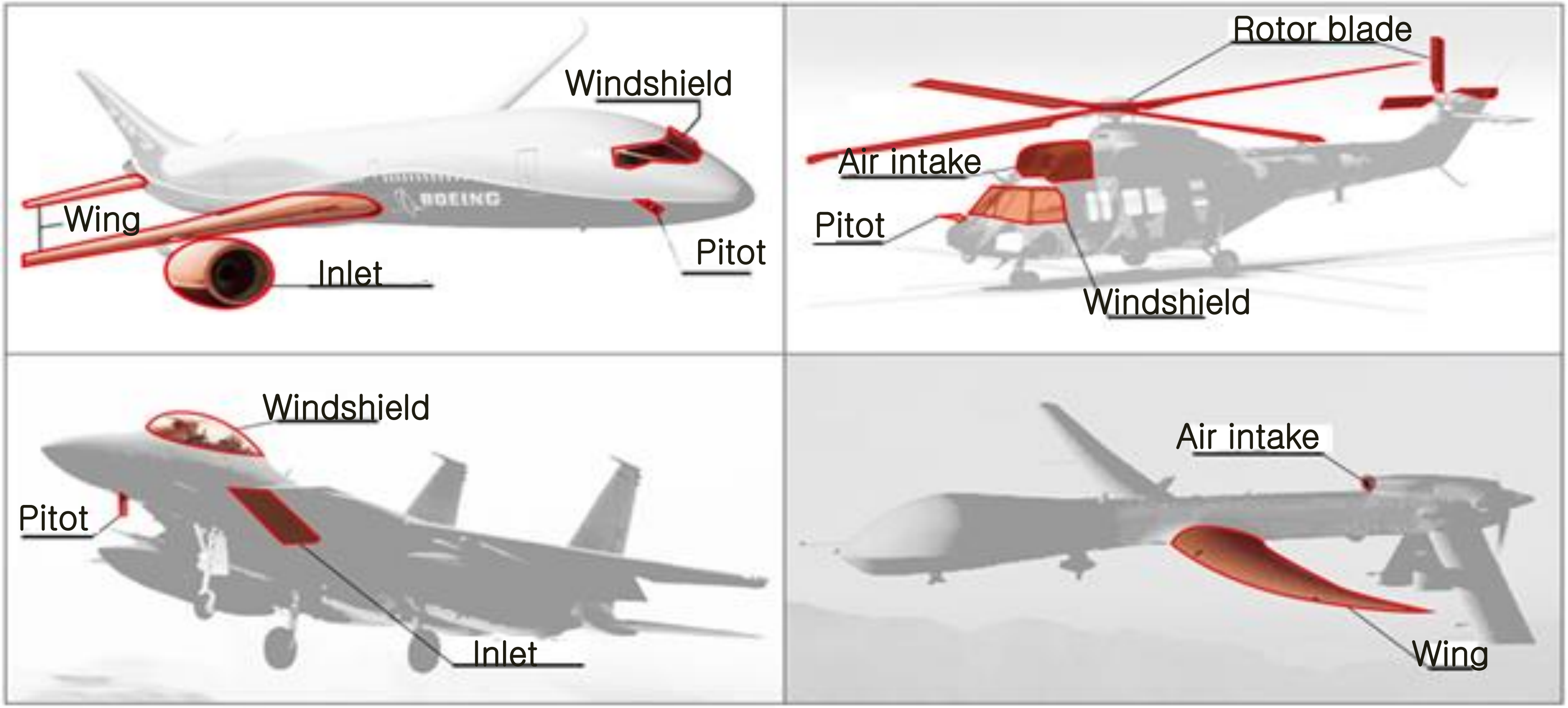
Mach Number 8.5

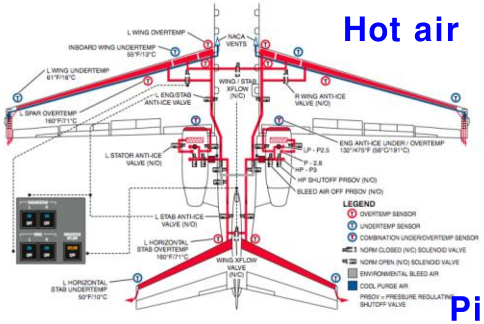
400 hours on 26 processors (DSMC)

vs

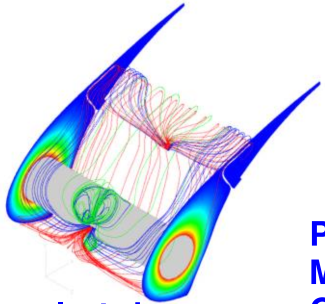
20 hours on single processor (new solver)

린치핀: 결빙보호 설계 1



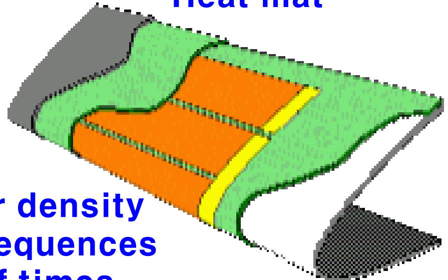


Hot air



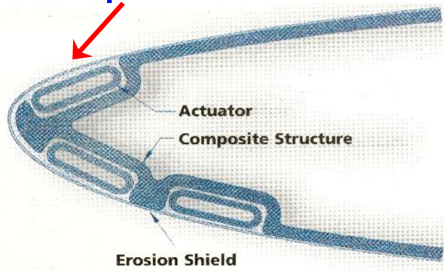
Piccolo tube

Heat mat



Power density
Mat sequences
On/off times

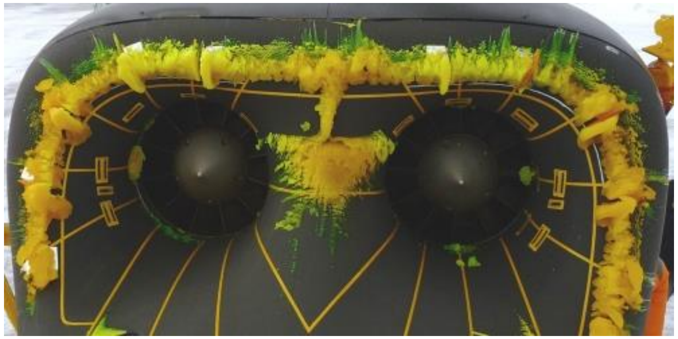
Impulse



린치핀: 결빙보호 설계 2

A critical redesign of IPS

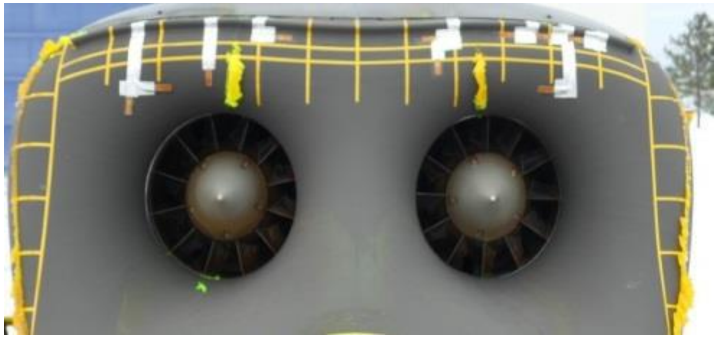
More than 130g for 2 minutes



Season 2015-16

Removing runback ice

Higher surface temperature
More time for evaporation
Longer distance for evaporation



Season 2017-18

Clearance of ice shedding of windshield & wiper

Season 2017-18

Courtesy of Korea Aerospace Industries LTD (KAI) (2018)

린치핀: 결빙보호 설계 3

Equations for clean air

$$\begin{bmatrix}\rho_g\\ \rho_g\mathbf{u}_g\\ E\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\rho_g\mathbf{u}_g\\ \rho_g\mathbf{u}_g\mathbf{u}_g+p\mathbf{I}\\ (E+p)\mathbf{u}_g\end{bmatrix} = \nabla\cdot\begin{bmatrix}0\\ \boldsymbol{\tau}\\ \boldsymbol{\tau}\cdot\mathbf{u}_g+\mathbf{Q}\end{bmatrix},\quad \begin{matrix}\boldsymbol{\tau}=2\mu\left[\nabla\mathbf{u}_g\right]^{(2)}\\ \mathbf{Q}=k\nabla T\end{matrix}$$

Shear stress
Heat flux

Equations for droplets

$$\begin{bmatrix}\rho\\ \rho\mathbf{u}\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\rho\mathbf{u}\\ \rho\mathbf{u}\mathbf{u}+\rho g d\mathbf{I}\end{bmatrix} = \begin{bmatrix}0\\ \mathbf{S}_D+\mathbf{S}_G+\mathbf{S}_S\end{bmatrix}$$

Droplet impact velocity
Collection efficiency

Equations for ice accretion

$$\begin{bmatrix}h_f\\ h_f T_{equi}\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\dfrac{h_f^2}{2\mu_w}\tau_{wall}\\ \dfrac{h_f^2 T_{equi}}{2\mu_w}\tau_{wall}\end{bmatrix} = \begin{bmatrix}\dfrac{S_M}{\rho_w}\\ \dfrac{S_E}{\rho_w Cp_{,w}}+\dfrac{T_c S_M}{\rho_w}\end{bmatrix}$$

$$S_M = U_\infty LWC_\infty\beta - \dot{m}_{evap} - \dot{m}_{ice}$$

$$S_E = \left[Cp_{,w}\tilde{T}_{d,\infty} + \frac{\left\|\vec{u}_d\right\|^2}{2}\right]\times U_\infty LWC_\infty\beta - L_{evap}\dot{m}_{evap}$$

$$+\dot{m}_{ice}\left[L_{fus} - Cp_{,ice}T_{equi}\right] + h_c\left(T_{equi} - T_\infty\right)$$

$$+\sigma_o\varepsilon\left[T_{equi}^4 - T_\infty{}^4\right]$$

$$h_f \ge 0, \dot{m}_{ice} \ge 0, h_f T_{equi} \ge h_f T_C, \dot{m}_{ice}T_{equi} \le \dot{m}_{ice}T_C$$

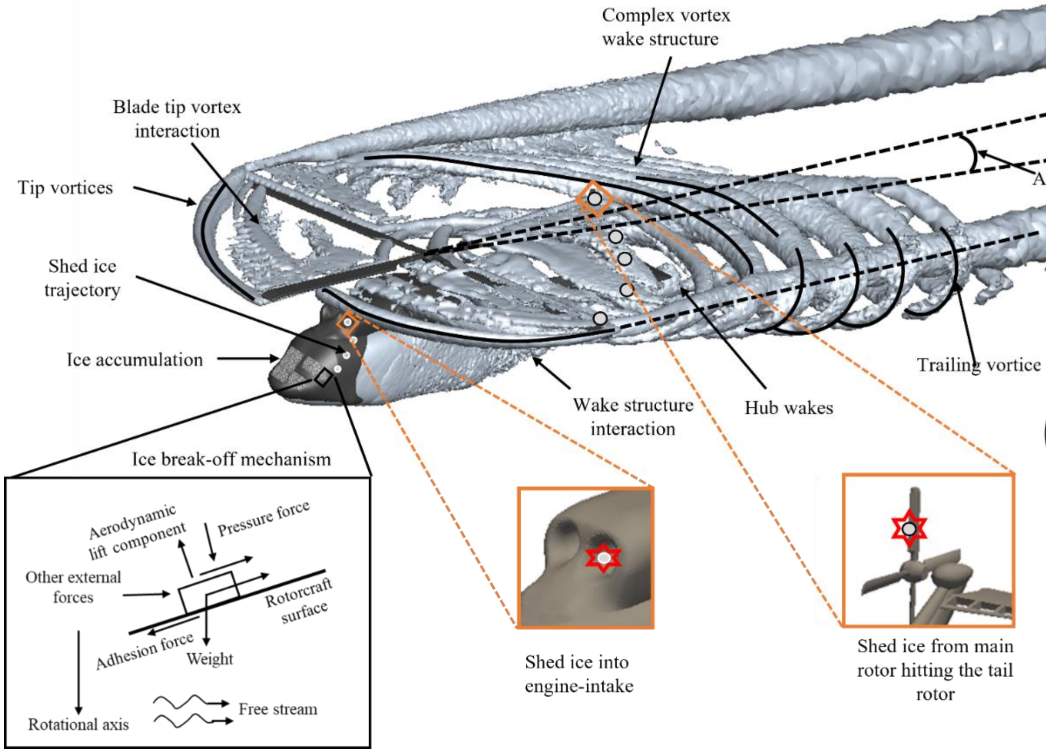
Conjugate (convection-conduction-convection) heat transfer

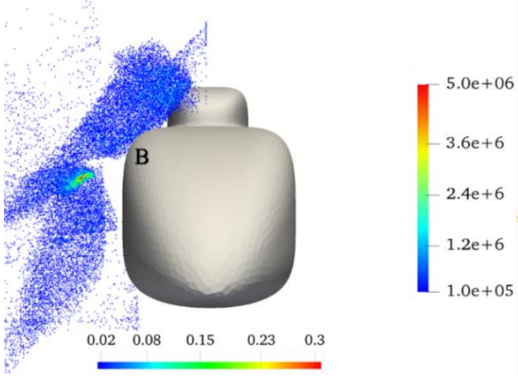
Equations for conductive heat transfer

$$\rho_s C_p(\Delta T)_t = \nabla\cdot\mathbf{Q} - \rho_s(\Delta H/\Delta T),\quad \mathbf{Q} = k_s\nabla(\Delta T)$$

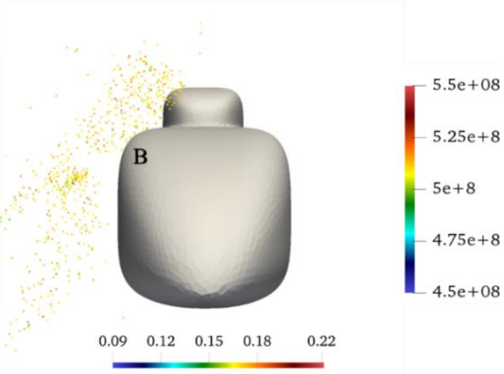
Poor rotor wake capturing: CFD suffers from excessive numerical dissipation on coarse grids; hence, wake structure and vorticity tend to dissipate rapidly after shedding from rotating blades.

린치핀: 결빙보호 설계 4

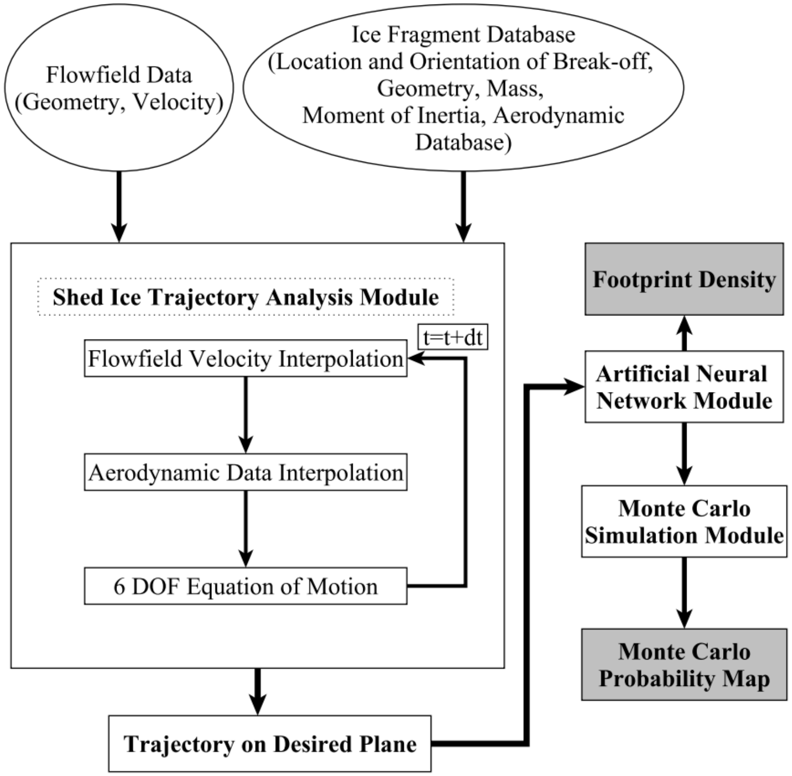




Footprint density



MC probability map



Flowfield Data (Geometry, Velocity)

Ice Fragment Database (Location and Orientation of Break-off, Geometry, Mass, Moment of Inertia, Aerodynamic Database)

Shed Ice Trajectory Analysis Module

Flowfield Velocity Interpolation

t=t+dt

Aerodynamic Data Interpolation

6 DOF Equation of Motion

Trajectory on Desired Plane

Artificial Neural Network Module

Footprint Density

Monte Carlo Simulation Module

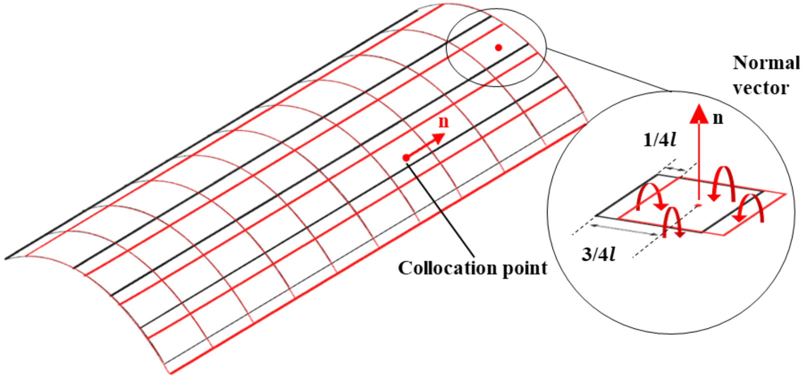
Monte Carlo Probability Map

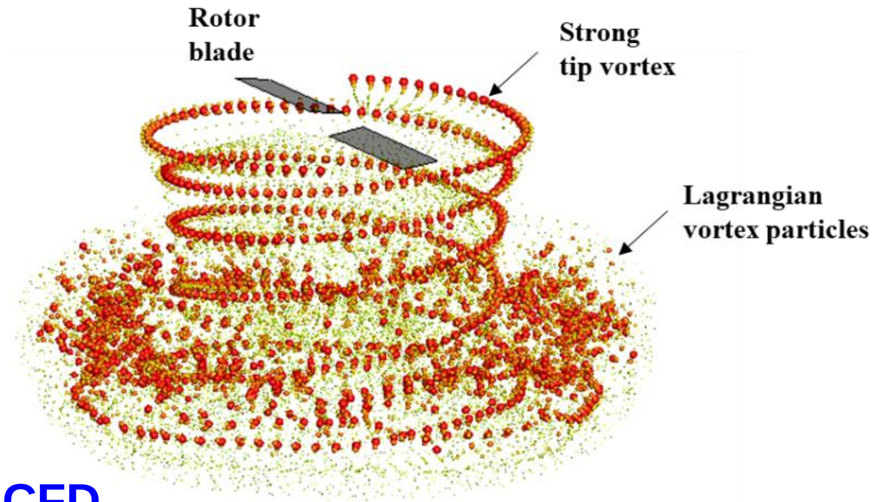
린치핀: 결빙보호 설계 5

VPM (Vortex Particle Method)

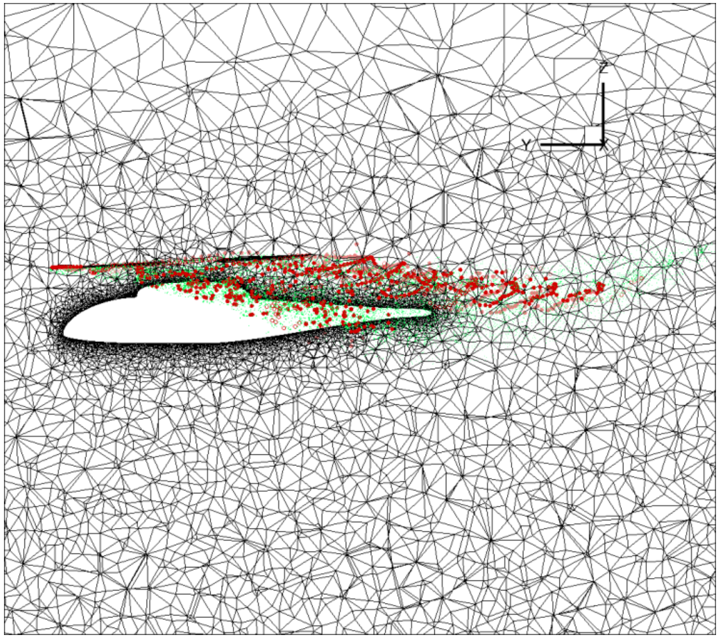
$$\frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega}\cdot\nabla)\mathbf{u} - \boldsymbol{\omega}(\nabla\cdot\mathbf{u}) + \frac{\mu}{\rho}\nabla^2\boldsymbol{\omega}$$

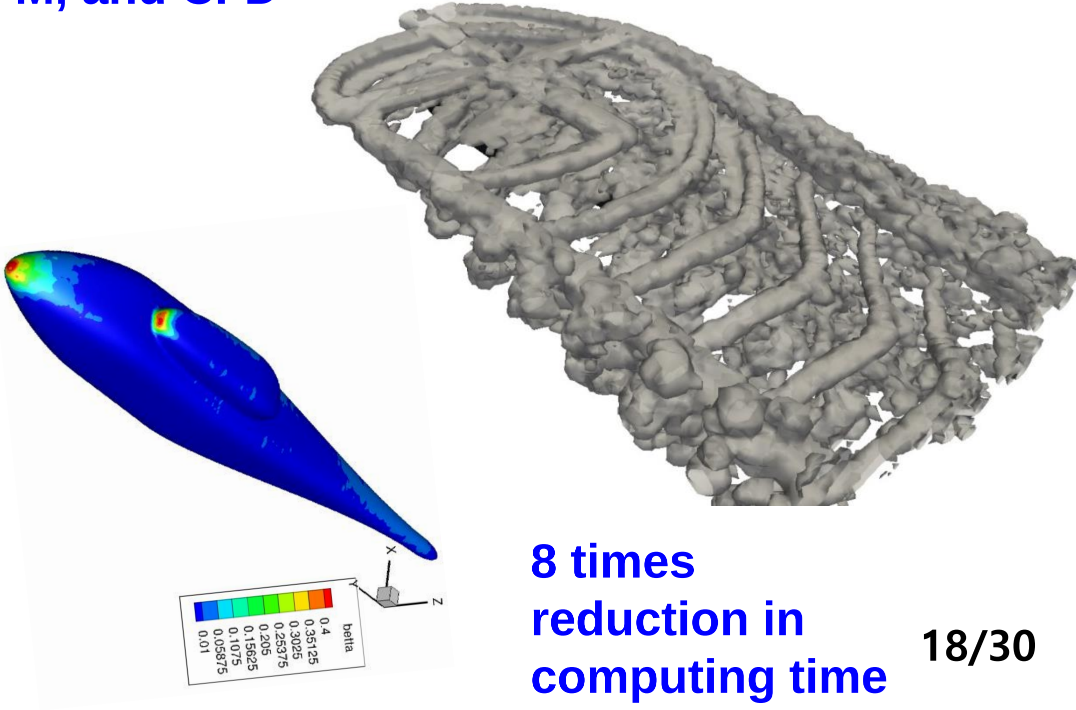
NVLM (Nonlinear Vortex Lattice Method)





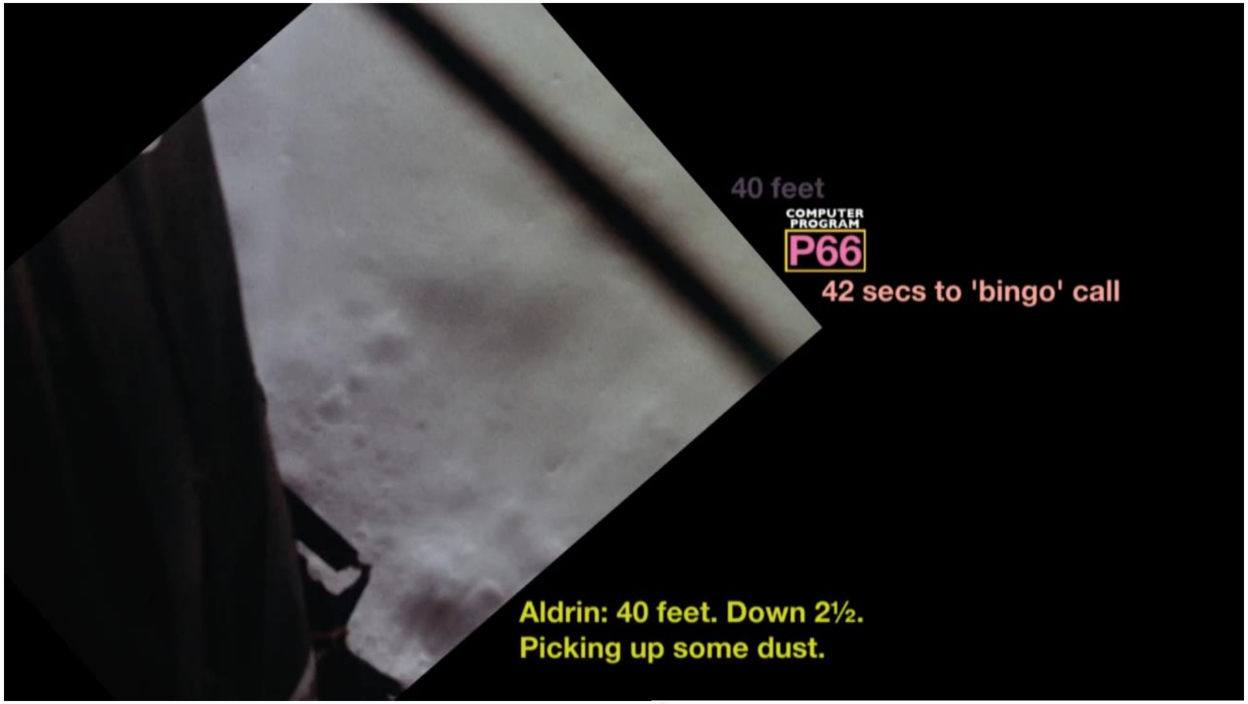
Hybrid method based on NVLM, VPM, and CFD





8 times reduction in computing time

린치핀: 달착륙 플룸-Regolith 상호작용 1



Aldrin: 40 feet. Down 2½.
Picking up some dust.

Lunar landing of Apollo 11
(1969년 7월 20일)

US Intuitive Machines
(2024년 2월 22일)

FEBRUARY 29, 2024

Private US moon lander still working after breaking leg and falling, but not for long

by Marcia Dunn

린치핀: 달착륙 플룸-Regolith 상호작용 2

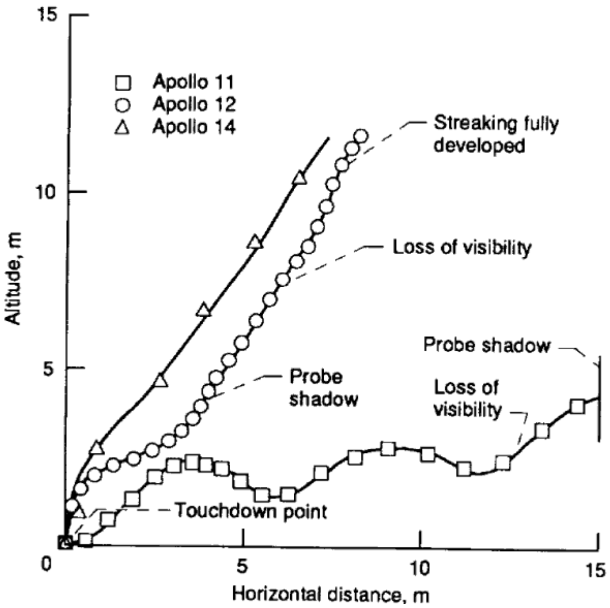
Physical damage to lander and sensors

Blocking vision, mal-function of tracking sensor of landing velocity and camera

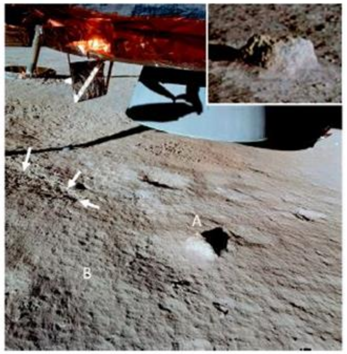
Trouble in exploration (degradation in thermal-control, dust contamination)

Apollo Astronaut John Young

“Dust is the number one concern in returning to the moon!”



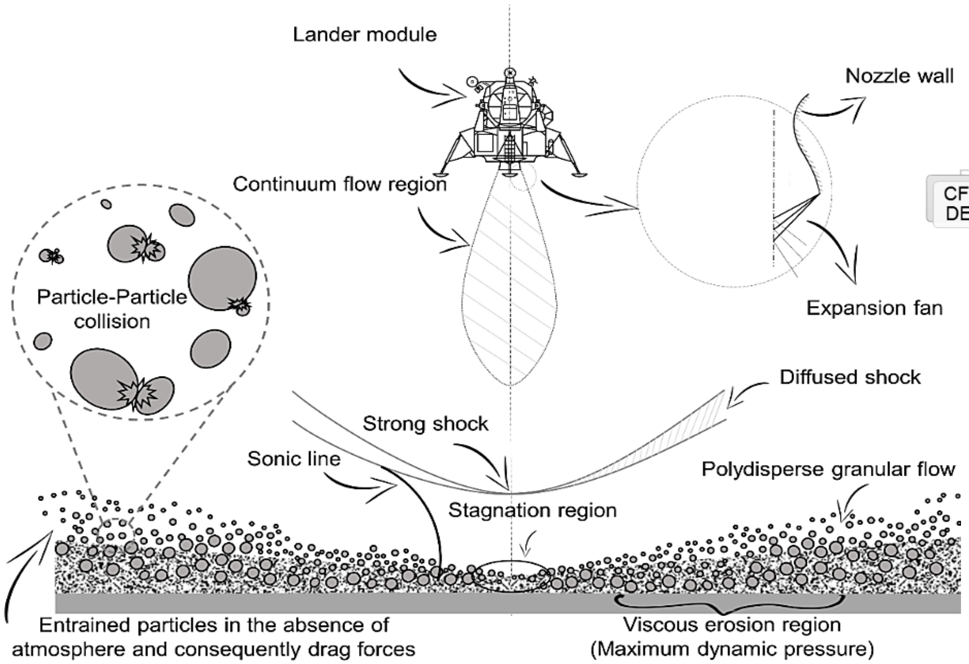
First Lunar landing
(Apollo 11)

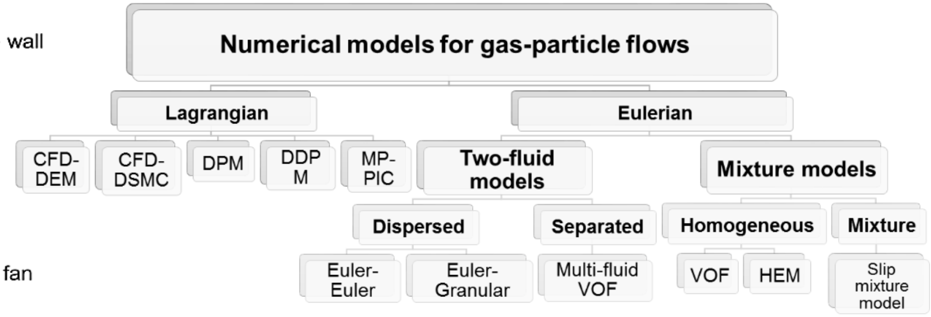


Apollo 14 surface
(NASA photograph AS14-66-9261HR)

Lunar surface

린치핀: 달착륙 플룸-Regolith 상호작용 3




Numerical models for gas-particle flows

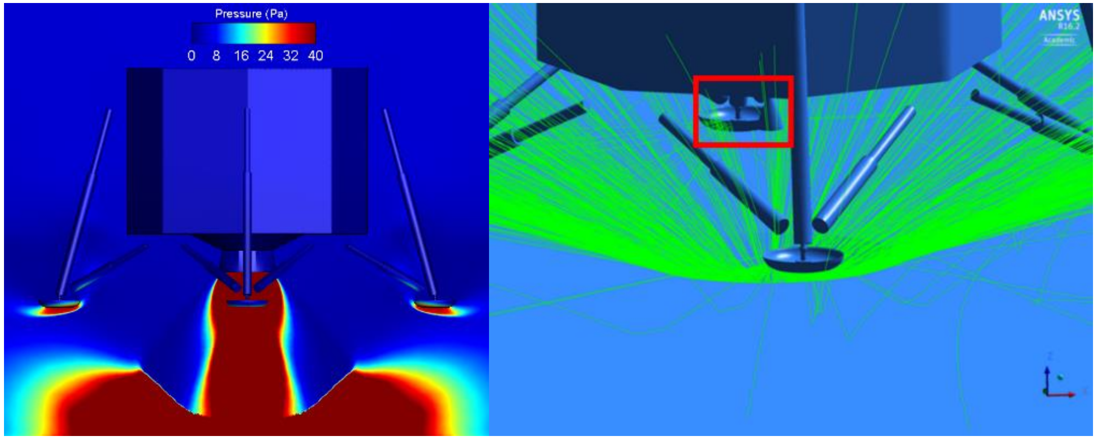
- **Lagrangian**
  - CFD-DEM
  - CFD-DSMC
  - DPM
  - DDPM
  - MP-PIC
- **Eulerian**
  - **Two-fluid models**
    - **Dispersed**
      - Euler-Euler
      - Euler-Granular
    - **Separated**
      - Multi-fluid VOF
  - **Mixture models**
    - **Homogeneous**
      - VOF
      - HEM
    - **Mixture**
      - Slip mixture model

$$\begin{bmatrix} \alpha_g\rho_g \\ \alpha_g\rho_g\mathbf{u}_g \\ \alpha_g\rho_g E_g \end{bmatrix}_t + \nabla\cdot\begin{bmatrix} \alpha_g\rho_g\mathbf{u}_g \\ \alpha_g\rho_g\mathbf{u}_g\mathbf{u}_g + p_g\mathbf{I} + \mathbf{\Pi}_g \\ (\alpha_g\rho_g E_g + p_g)\mathbf{u}_g + \mathbf{\Pi}_g\cdot\mathbf{u}_g + \mathbf{Q}_g \end{bmatrix} =$$

$$\nabla\cdot\begin{bmatrix} 0 \\ D_{g,s}(\mathbf{u}_s - \mathbf{u}_g) \\ D_{g,s}(\mathbf{u}_s - \mathbf{u}_g)\cdot\mathbf{u}_s + Q_{g,s}(T_s - T_g) \end{bmatrix},$$

$$\begin{bmatrix} \alpha_s\rho_s \\ \alpha_s\rho_s\mathbf{u}_s \\ \alpha_s\rho_s E_s \\ \alpha_s\rho_s e_s \end{bmatrix}_t + \nabla\cdot\begin{bmatrix} \alpha_s\rho_s\mathbf{u}_s \\ \alpha_s\rho_s\mathbf{u}_s\mathbf{u}_s + p_s\mathbf{I} + \mathbf{\Pi}_s \\ (\alpha_s\rho_s E_s + p_s)\mathbf{u}_s + \mathbf{\Pi}_s\cdot\mathbf{u}_s + \mathbf{Q}_s \\ \alpha_s\rho_s e_s\mathbf{u}_s \end{bmatrix} =$$

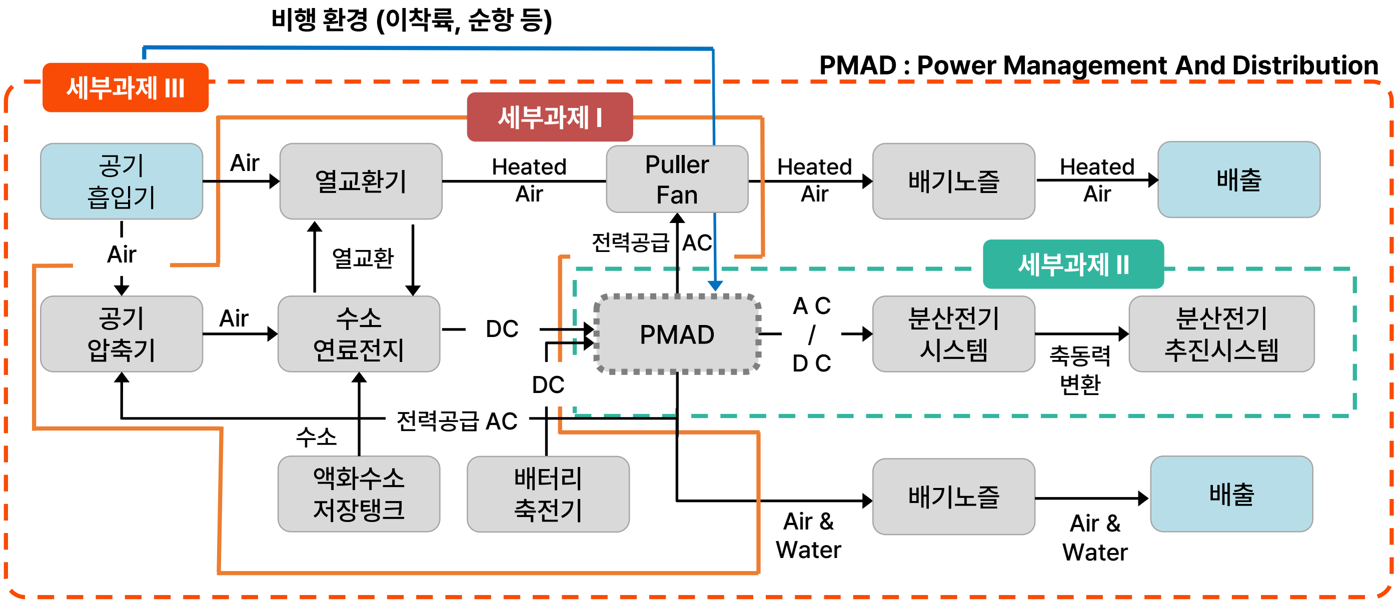
$$\nabla\cdot\begin{bmatrix} 0 \\ D_{g,s}(\mathbf{u}_s - \mathbf{u}_g) \\ D_{g,s}(\mathbf{u}_s - \mathbf{u}_g)\cdot\mathbf{u}_s + Q_{g,s}(T_s - T_g) \\ \dot{\gamma} \end{bmatrix}$$



한국형 달착륙선 착륙기술
(우주핵심연구 2017년)

플래그십: 수소연료전지 항공기 1

과제명	수소연료전지 기반 하이브리드 분산 전기추진 시스템을 활용한 커뮤터기 기술
국가전략기술	미래도전 우주항공·해양과 수소, 혁신선도 첨단 모빌리티, 혁신선도 이차전지
주관기관	경상국립대학교
공동기관	UNIST, 경남대학교, 울산대학교, 한국전기연구원, 한국항공우주산업(주), 한화에어로스페이스(주), (주)삼현, (주)에스더블유이노베이션, (재)경남테크노파크
지자체및위탁기관	경상남도, 울산광역시, 특허법인 PCR
개발비	총 85.57억원 (국고 55억원, 지자체 22억원, 기관부담 8.57억원)
지원기관	과학기술정보통신부 연구개발특구진흥재단


비행 환경 (이착륙, 순항 등)

PMAD : Power Management And Distribution

세부과제 III

세부과제 I

세부과제 II

공기 흡입기

Air

열교환기

Heated Air

Puller Fan

Heated Air

배기노즐

Heated Air

배출

Air

열교환

전력공급

AC

공기 압축기

Air

수소 연료전지

DC

PMAD

A C / D C

분산전기 시스템

축동력 변환

분산전기 추진시스템

DC

수소

전력공급 AC

액화수소 저장탱크

배터리 축전기

Air & Water

배기노즐

Air & Water

배출

플래그십: 수소연료전지 항공기 2

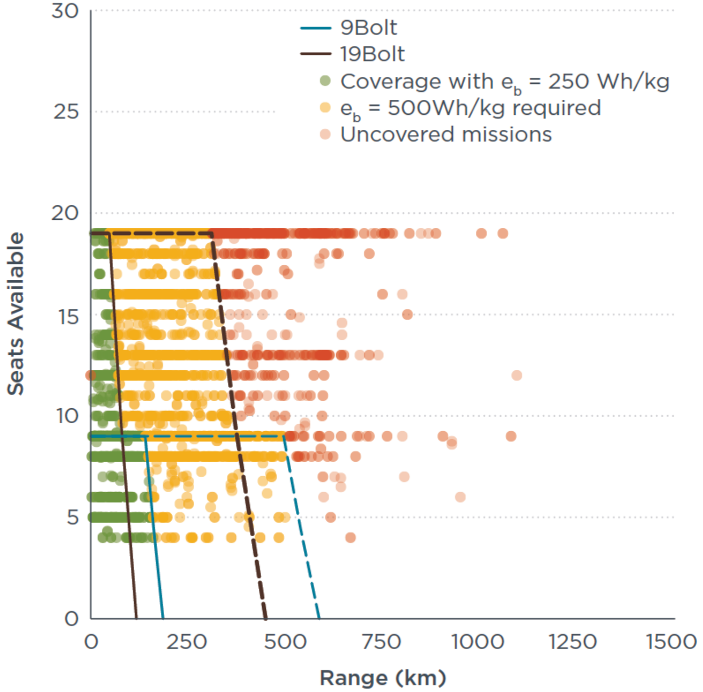
1,000km 이하는 승객 수 기준 57%가 전기추진 항공기로 대체될 예정

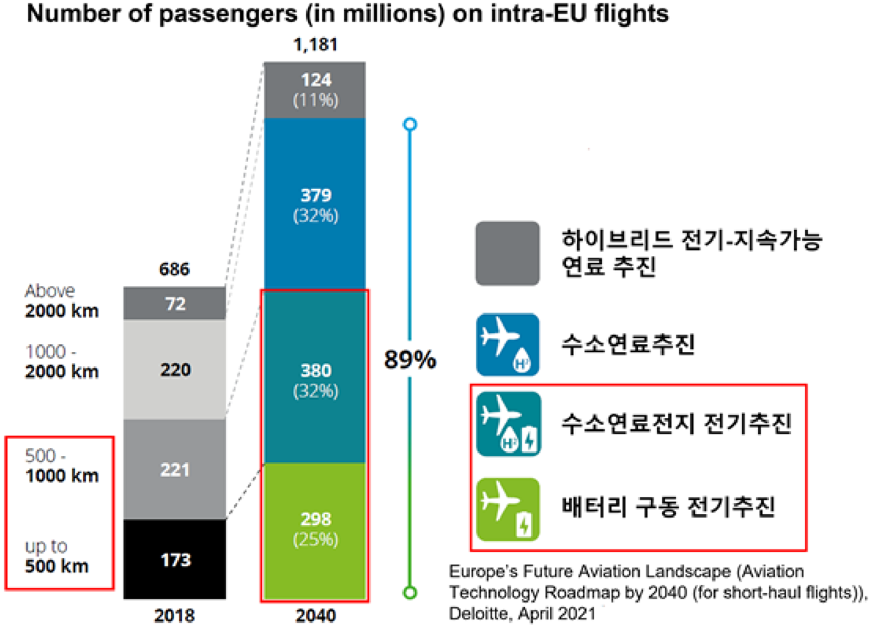
친환경 저탄소 항공기 개발은 "**선택이 아닌 생존의 문제**"

"기울어진 운동장"이 아닌 "평평한 운동장"에서 **민수 항공기 시장을 선점할 수 있는 유일한 기회**

One of Europe's busiest airports to be forced to cut flights due to planet-warming carbon pollution

Xiaofei Xu, CNN
Published 1:58 PM EDT, Wed March 22, 2023



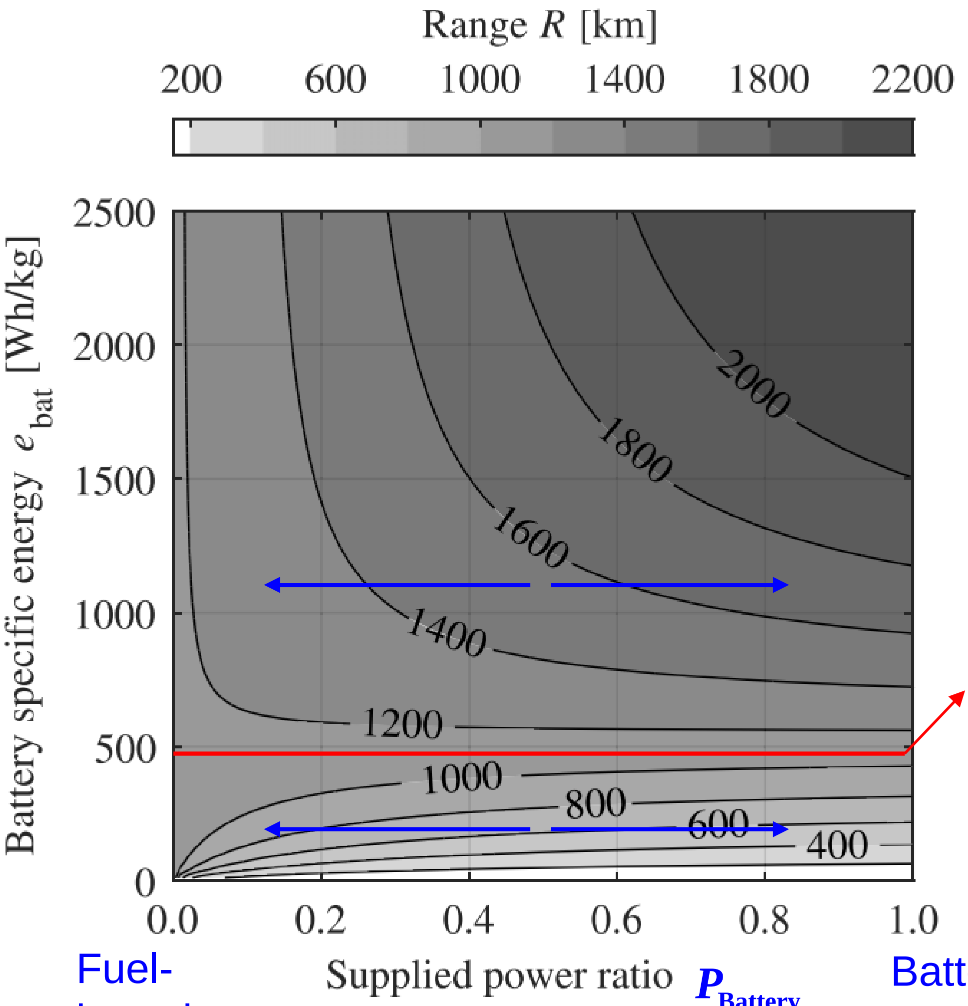


Europe's Future Aviation Landscape (Aviation Technology Roadmap by 2040 (for short-haul flights)), Deloitte, April 2021

Requirements

19 Passenger (Part 23), Range (500~1,000 km), Payload (30%), TO/Landing Distance (500~800 m), Carbon Reduction (75~90%), Low Noise (Below 75 dB)

플래그십: 수소연료전지 항공기 3



$$\frac{P_{Battery}}{P_{Battery}+P_{Fuel}}$$

Fuel-based

Battery-based

Fuel cell only

$$\eta_{prop} e_{fuel} \frac{C_L}{C_D} \eta_{fuel-cell} \mathbf{Log_{exp}} \left(\frac{W_{empty} + W_{payload} + W_{fuel}}{W_{empty} + W_{payload}} \right)$$

Hybrid

$$\eta_{prop} e_{battery} \frac{C_L}{C_D} \eta_{elec.-motor} \left(\frac{W_{empty} + W_{payload} + W_{fuel}}{W_{empty} + W_{payload}} \right)$$

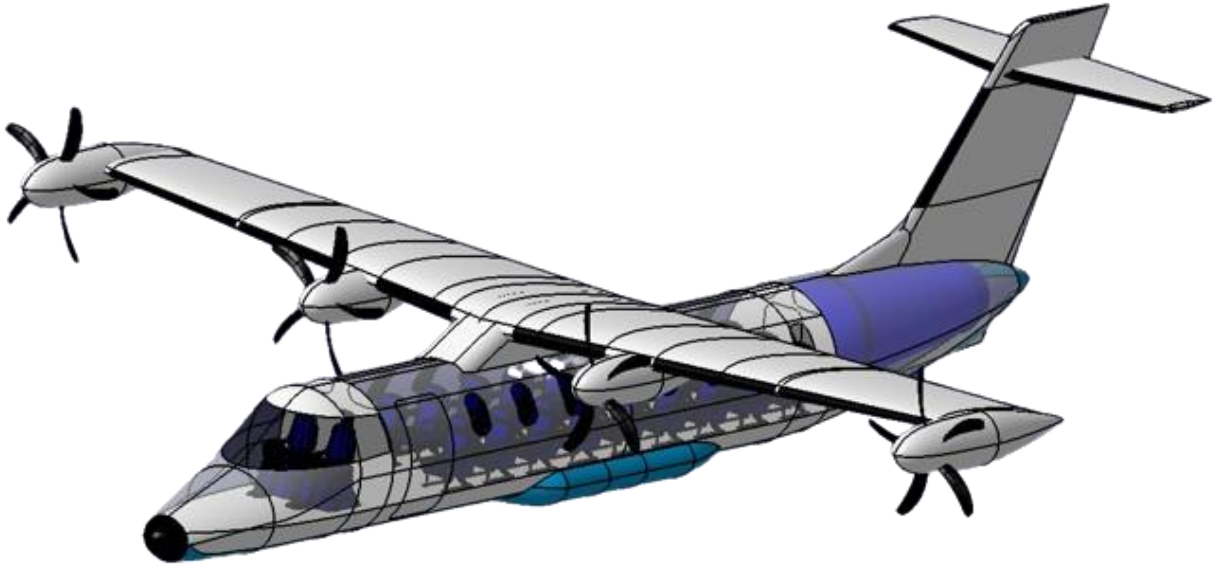
Battery only

High transmission efficiency of the electrical powertrain branch leading to an energy saving that offsets the weight penalty of the batteries

Dividing line depending on the weight breakdown and the transmission efficiency of the powertrain

High energy density of fuel compensating the lower conversion efficiency

플래그십: 수소연료전지 항공기 4

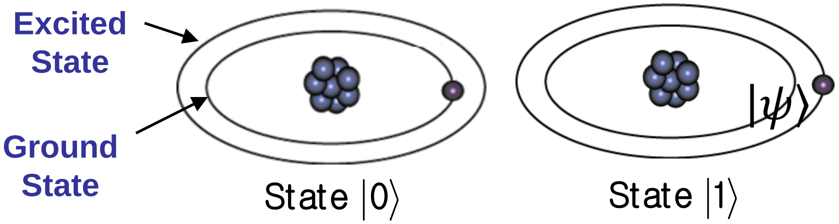


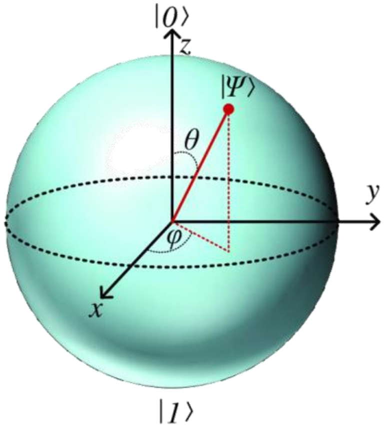
Hybrid power system	Fuel cell power system considering low-density flight environments
Distributed electric propulsion system	High-fidelity methods for computing air flows over wing-fuselage-propeller
High performance commuter	High-lift, low-noise aerodynamic shape design

전망: Quantum CFD 1

Quantum Computing Concepts: Superposition, Entanglement, Measurement, Unitary ($UU^\dagger=I$) Operators

Challenges Toward QCFD: Non-linear term, Non-unitary operator, Elementwise Multiplication





Qubit

Bit

State Vector: $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle \qquad |\alpha|^2+|\beta|^2=1$

$$
\begin{aligned}
|\psi\rangle &= |\psi_1\rangle\otimes|\psi_2\rangle \\
&= (\alpha_1|0\rangle+\beta_1|1\rangle)\otimes(\alpha_2|0\rangle+\beta_2|1\rangle) \\
&= \alpha_1\alpha_2|00\rangle+\alpha_1\beta_2|01\rangle+\beta_1\alpha_2|10\rangle+\beta_1\beta_2|11\rangle
\end{aligned}
$$

$$\alpha|0\rangle+\beta|1\rangle \;\text{———}\boxed{X}\text{———}\; \beta|0\rangle+\alpha|1\rangle$$

Quantum NOT gate

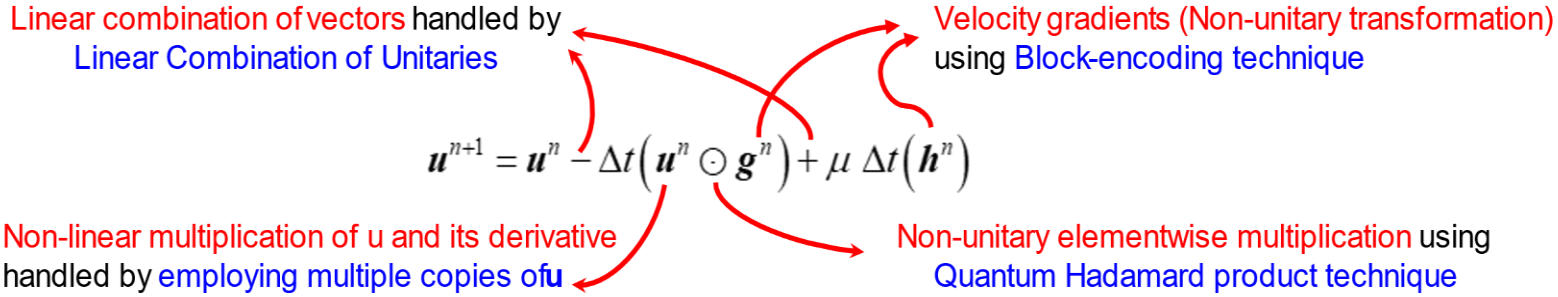
$$|00\rangle=|0\rangle\otimes|0\rangle=\begin{bmatrix}1\\0\end{bmatrix}\otimes\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}1&0&0&0\end{bmatrix}^T \quad |01\rangle=|0\rangle\otimes|1\rangle=\begin{bmatrix}1\\0\end{bmatrix}\otimes\begin{bmatrix}0\\1\end{bmatrix}=\begin{bmatrix}0&1&0&0\end{bmatrix}^T$$

$$|10\rangle=|1\rangle\otimes|0\rangle=\begin{bmatrix}0\\1\end{bmatrix}\otimes\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}0&0&1&0\end{bmatrix}^T \quad |11\rangle=|1\rangle\otimes|1\rangle=\begin{bmatrix}0\\1\end{bmatrix}\otimes\begin{bmatrix}0\\1\end{bmatrix}=\begin{bmatrix}0&0&0&1\end{bmatrix}^T$$

전망: Quantum CFD 2

Burger's equation is the best model to study nonlinearity in compressible flow.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \mu\frac{\partial^2 u}{\partial x^2}$$



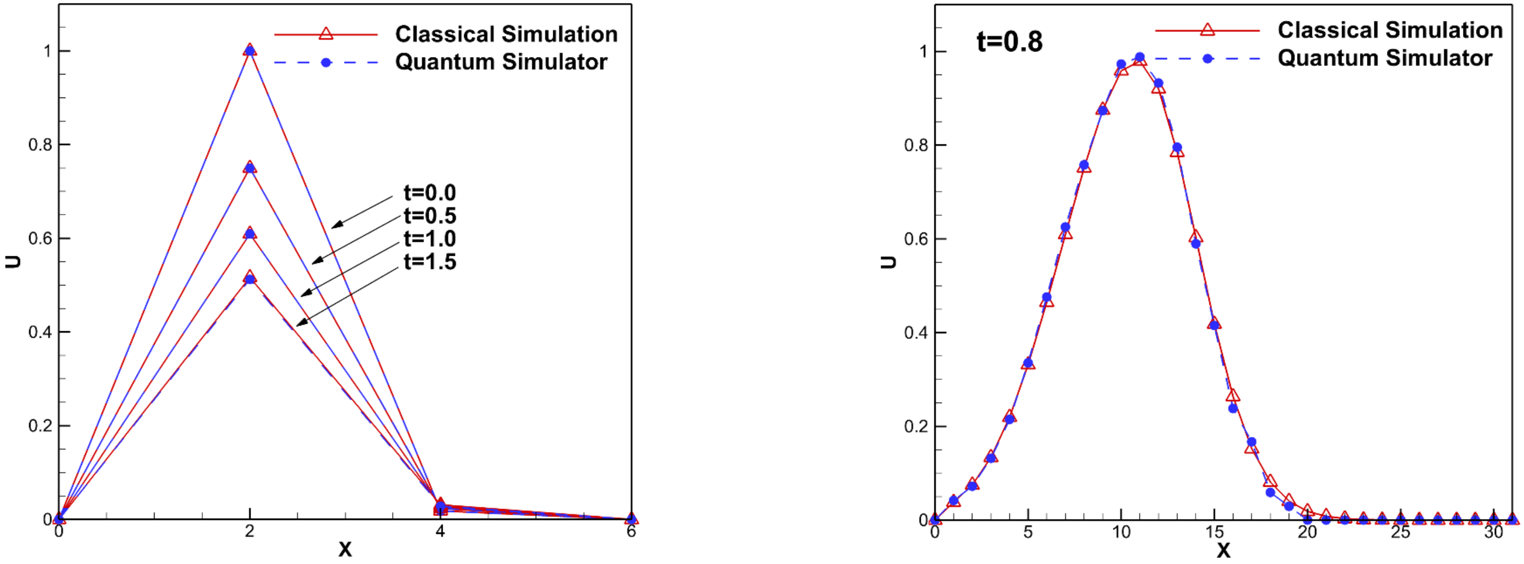
Linear combination of vectors handled by Linear Combination of Unitaries

Velocity gradients (Non-unitary transformation) using Block-encoding technique

$$\boldsymbol{u}^{n+1} = \boldsymbol{u}^{n} - \Delta t\left(\boldsymbol{u}^{n} \odot \boldsymbol{g}^{n}\right) + \mu\,\Delta t\left(\boldsymbol{h}^{n}\right)$$

Non-linear multiplication of u and its derivative handled by employing multiple copies of **u**

Non-unitary elementwise multiplication using Quantum Hadamard product technique



“Pure Quantum Algorithm of Nonlinear Burgers’ Equation for High-Speed Compressible Flows,” *Preprint*

전망: KASA AeSp Data & Computing Center

비전

우주항공 도전적 임무 달성을 위한 혁신 Data & Computing 기술 개발

집단연구 역할

혁신적 Seed 기반 과학기술 선점, 장기적 연구개발 수행, 기술사업화

추진체계

기존 집단연구: 원천기술, 기술이전·사업화
(기업 컨소시엄 또는 공동기관)

vs

미래 KASA 집단연구: 대학-연구소-수요기업

전망: 신규 우주탐사 플래그십 1

Original Flagship Idea (Need to select through competition from ideas of various organizations and individuals)

Challenging Mission with Controllable Cost

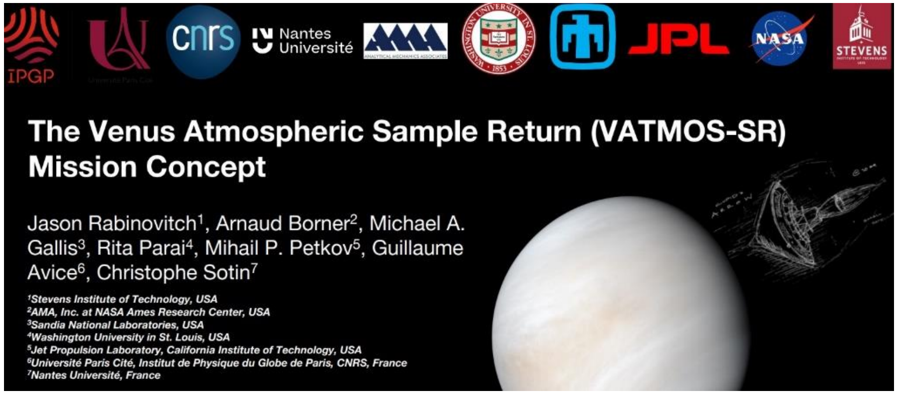
Connecting Science and Technology

금성(Venus) 표면 관측 및 대기 샘플 리턴(Sample Return)

- **금성 대기(지구대기 90배 밀도)의 기원, 진화, 기후 역사 연구, 금성 대기, 표면, 내부의 상호작용 규명**
- **지구와 여러 면에서 유사한 쌍둥이 행성인 금성에 대한 비교 연구를 통해 지구와 태양계 행성의 역사와 생명체 환경에 대한 지식 확장**
- **일본 Akatsuki (진행중), 인도 Shukrayaan (24년 12월 발사 예정), 미국 DAVINCI 2029 및 VERITAS 2031, ESA EnVision 2031**
- **국내에서는 시도되지 되지 않은 도전적 임무 (과학과 기술 두 측면에서 모두 도전적)**
- **최신 레이다를 통한 정밀(저 고도) 금성 표면 관측 이외에 1) 이온엔진을 사용한 초 저궤도 비행 기술 개발을 통해 고도 약 130 km에서의 대기가스 (15 km/s 속도) 채집; 2) 밀봉 상태로 보관 후 지구 재진입을 통해 샘플 리턴을 달성하는 것이 전 세계적으로도 독창적임**
- **우주 도전에 동참(국격 신장)하는 동시에 초 저궤도 위성 기술과 재진입 기술 확보가 가능 (2030-40)**

전망: 신규 우주탐사 플래그십 2

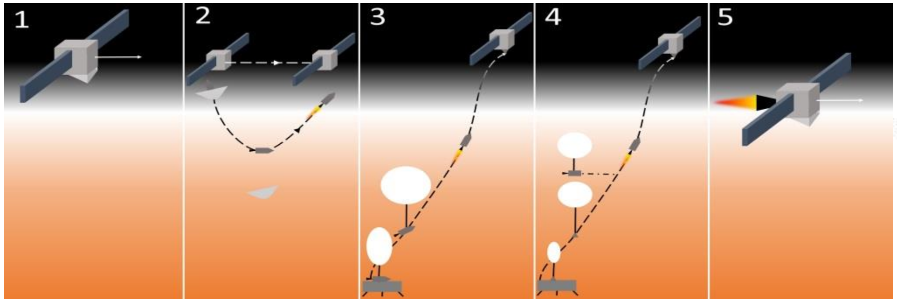
US VATMOS-SR (2020s)



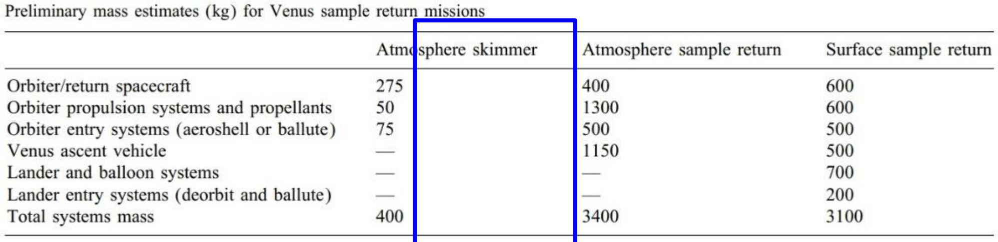
The Venus Atmospheric Sample Return (VATMOS-SR) Mission Concept

Jason Rabinovitch[1], Arnaud Borner[2], Michael A. Gallis[3], Rita Parai[4], Mihail P. Petkov[5], Guillaume Avice[6], Christophe Sotin[7]

[1]Stevens Institute of Technology, USA
[2]AMA, Inc. at NASA Ames Research Center, USA
[3]Sandia National Laboratories, USA
[4]Washington University in St. Louis, USA
[5]Jet Propulsion Laboratory, California Institute of Technology, USA
[6]Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, France
[7]Nantes Université, France



New Venus Super Low Altitude Exploration & Sample Return (2030~40)

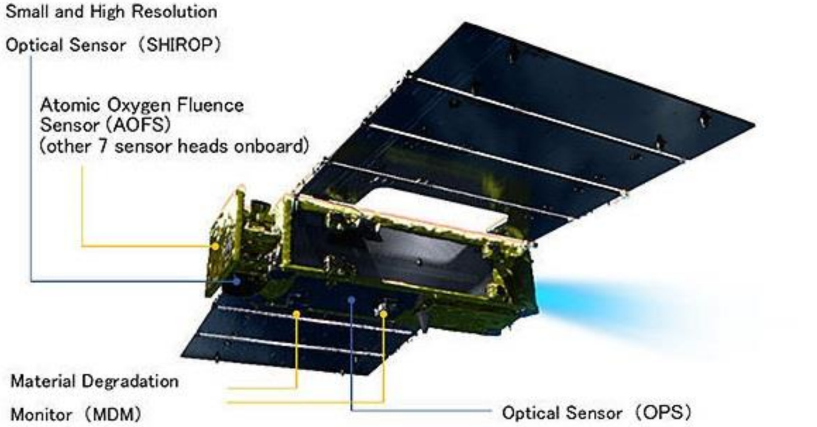


Preliminary mass estimates (kg) for Venus sample return missions

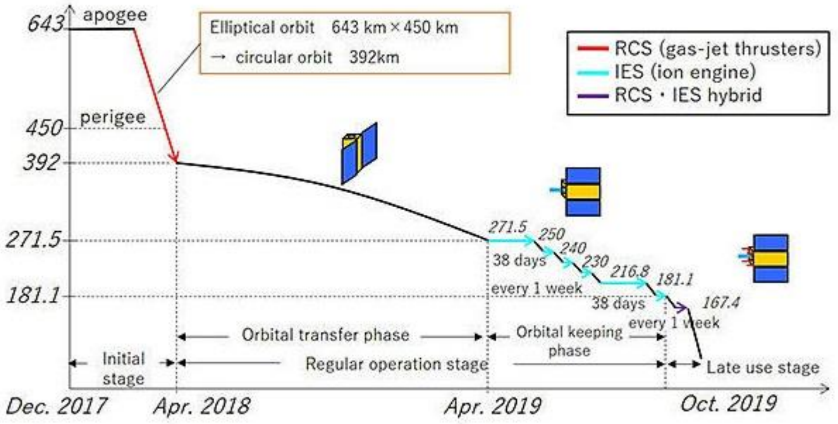
	Atmosphere skimmer	Atmosphere sample return	Surface sample return
Orbiter/return spacecraft	275	400	600
Orbiter propulsion systems and propellants	50	1300	600
Orbiter entry systems (aeroshell or ballute)	75	500	500
Venus ascent vehicle	—	1150	500
Lander and balloon systems	—	—	700
Lander entry systems (deorbit and ballute)	—	—	200
Total systems mass	400	3400	3100

1500-2000 kg

[Illustration of Tsubame in orbit]



SLATS Orbital Profile]



※ Orbital altitude = Average semi-major axis - Equatorial radius

Super Low Altitude Test Satellite (JAXA, Japan, 30 Dec 2019)