Transient Behaviour Modelling of Liquid Rocket Engine Components

Von der Fakultät für Maschinenwesen der
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zur Erlangung des akademischen Grades
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vorgelegt von

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ai miei genitori

Hiding in the deepest corners
of my mind, I spin a web
to seize my impossible dream
destroying myself with every
successive thread of silk consumed
until I am born anew.

Erminea

Contents

Nomenclature

Latin Symbols:

a	speed of sound	m/s
a, b, c	constants	-
A	cross-sectional area	m^2
$A^\star$	unsteady friction constant (Annex A)	-
c^*	characteristic velocity	m/s
c_0	spouting velocity	m/s
C	discharge coefficient	-
C_f	fluid capacitance	m^5/N
c_p	constant pressure specific heat	J/(kg K)
c_v	constant temperature specific heat	J/(kg K)
$C^\star$	unsteady friction constant (Annex A)	-
C_t	thermal capacitance	J/K
d	diameter	m
$erf(x)$	error function ($erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$, Annex A)	-
E	YOUNG's modulus	Pa
f	FANNING friction coefficient	-
F	force	N
F	thrust	N
h	height	m
h	specific enthalpy	J/kg
H	head	m
I_f	fluid inductance	kg/m^4
I_{sp}	specific impulse	s
k	thermal conductivity	W/mK
K_L	loss coefficient	-
l	length	m
L^*	characteristic length	m
m	mass	kg
$\dot{m}$	mass flow	kg/s
Ma	MACH-number ($Ma = v/a$)	-
M_R	mixture ratio	-
n	LOCKHART-MARTINELLI coefficient	-

n_s	specific speed	-
N_B	BIOT number ($N_B = hL/k$)	-
S	surface area	m^2
p	pressure	Pa
r	radius	m
r_c	recovery factor	-
r_d	diameter ratio	m
R_f	hydraulic fluid resistance	kg/m^4s
$\mathcal{R}$	specific gas constant	J/(kg K)
Re	REYNOLDS-number ($Re = \rho\, v\, d/\mu$)	-
$\dot{q}$	heat transfer per unit area	W/m^2
$\dot{Q}$	heat transfer	W
t	time	s
T	temperature	K
u	specific internal energy	J/kg
V	volume	m^3
$\dot{V}$	volume flow	m^3/s
$\dot{W}$	rate of work	J/s
x, y, z	CARTESIAN coordinates	m

Greek Symbols:

α	angle of inclination	rad.
α	throttle control drive position (Figure 3.19)	rad.
α	thermal diffusivity	m^2/s
α	void fraction (Equation 3.26)	-
β	angle of pitch	rad.
β	liquid-to-gas density ratio (Equation 3.26)	-
δ	thickness	m
Δ	difference	-
ϵ	expansion ratio ($\epsilon = A_e/A_t$)	-
ϵ	emissivity	-
ζ	loss coefficient due to section changes	-
η	efficiency	-
θ	angle	rad.
ϑ	POISSON's ratio	-
κ	ratio of specific heats	-

λ	friction factor	-
μ	dynamic viscosity	kg/(m s)
μ	flow coefficient	-
v	velocity (y-direction)	m/s
ξ	resistance coefficient	-
ρ	density	kg/m^3
σ	surface tension	N/m
τ	wall shear stress	N/m^2
τ	characteristic time	s
υ	velocity (x-direction)	m/s
ϕ	velocity coefficient	-
ψ_T	non-dimensional time (Annex A)	-
ω	rotational speed	rad/s

Subscripts:

0	total conditions
$1p$	one phase (flow)
∞	unconfined conditions
a	ambient
ad	adiabatic
b	break-up time
bt	break time
c	chamber
cap	capacitance
$cond$	conductive
$conv$	convective
$crit$	critical
d	dome
$damp$	damper
dyn	dynamic
e	exit
eng	engine
$fric$	friction
fu	fuel
g	gas
geo	geometry

gen	generated
hyd	hydraulic
id	ideal
ind	inductance
inj	injector
l	liquid
mix	mixture
mod	modified
nom	nominal
nzl	nozzle
$orif$	orifice
op	over-pressure
ox	oxidiser
p	piston
p	pressure
P	pump
r	radial
res	resistance
rd	reduced
ref	reference
reg	regulator
R	ratio
s	isentropic
s	specific
sat	saturation
sh	superheat
sl	sea level
sub	subsonic
sup	supersonic
sv	slide valve
t	thermal
t	throat
tng	tangential
thr	throttle
T	transient
T	turbine

u	unsteady
v	vacuum
v	volumetric
w	wall

Superscripts:

ss	steady state

Constants:

g_0	acceleration of gravity (standard)	$g_0 \approx 9,80665\,\mathrm{m/s^2}$
$\Re$	universal gas constant	$\Re \approx 8.3145\,\mathrm{J/(molK)}$
σ_B	STEFAN-BOLTZMANN constant	$\sigma_B \approx 5.6704 \cdot 10^{-8}\,\mathrm{W/m^2K^4}$

Acronyms:

2D	two-dimensional
3D	three-dimensional
CAD	computer aided design
CARS	Coherent anti-Stokes RAMAN Scattering Spectroscopy
CEA	Chemical Equilibrium with Applications (NASA Lewis Research Center combustion programme)
CFD	computational fluid dynamics
CFL	COURANT-FRIEDRICHS-LEWY
CNES	Centre National d'Etudes Spatiales (French Space Agency)
CPU	Central Processing Unit
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Research Center)
EPC	Étage Principal Cryogénique (Central stage of the Ariane 5)
EPS	Étage à Propergols Stockables (Upper stage of the Ariane 5 with storable propellants)
ESA	European Space Agency
FPOV	fuel preburner oxidiser valve
IMSL	International Mathematical Statistical Library
IVP	initial value problem
LH2	liquid hydrogen

LOx	liquid oxygen
LPM	lumped parameter method
LRE	liquid propellant rocket engine
MCC	main combustion chamber
MFV	main fuel valve
MMCo	mass flow mass flow combustor (system F)
MMOC	modified method of characteristics
MOC	method of characteristics
MOLIERE	tool for the MOdelling of LIquid rocket Engine tRansiEnts
MOV	main oxidiser valve
NASA	National Aeronautics and Space Administration (US Aerospace Agency)
NIST	National Institute of Standards and Technology
NTO	nitrogen tetraoxide
RP	RIEMANN problem
ODE	ordinary differential equation
ONERA	Office National d'Études et de Recherches Aérospatiales (French Aerospace Research Establishment)
OPOV	oxidiser preburner oxidiser valve
SSME	Space Shuttle Main Engine
TPDaP	tank pipe damper pipe (system C)
TPPT	tank pipe pipe tank (system A)
TPRPDo	tank pipe throttle pipe dome (system E)
TPRPT	tank pipe throttle pipe tank (system B)
TVD	total variation diminishing
WAF	weighted average flux