Current Zero Club

Fundamentals of current interruption in SF_6 and its alternative gases

Current Zero Club

International Research Group on Interruption Phenomena of Power Switching Devices

Current Zero Club

- International Research Group on Interruption Phenomena of Power Switching Devices

- Aligned with CIGRE Study Committee A3 (T&D equipment)

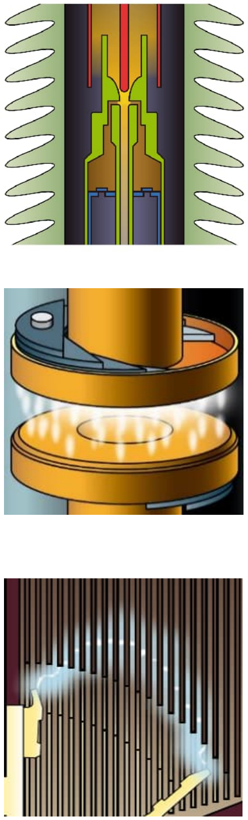
- 30 members (upon invitation) from industry and academia
  - Scientific and independent

- Founded in 1961

- Specialists' circles on dedicated topics:

  - Gas circle
  - Vacuum circle
  - Low-voltage circle

- http://currentzeroclub.org/
  Today’s presentation will be posted there and on e-cigre.org



phasetophase www.l-seven.nl

Content

- **Current Zero Club (CZC)**

  Dr. R. P. P. Smeets (KEMA Labs, Arnhem, the Netherlands)

- **Introduction**

  Dr. M. Seeger (Hitachi Energy Ltd., Switzerland)

- **Part 1: Introduction and physical processes**

  Prof. Dr. C.M. Franck (ETH Zürich, Switzerland)

  Prof. Dr. J.D. Yan (Univ. of Liverpool, United Kingdom)

- **Part 2: Comparison of properties of SF_6 alternative gases**

  Prof. Dr. J.D. Yan (Univ. of Liverpool, United Kingdom)

  Dr. M. Seeger (Hitachi Energy Ltd., Switzerland)

Introduction

- SF_6 has high Global Warming Potential (GWP) and long lifetime in the atmosphere, which makes it highly desirable to replace SF_6 in electric power equipment with environmentally friendly solutions
- In the recent years SF_6 alternative solutions for switching applications in transmission and distribution (T&D) have been identified using gas circuit breakers (Gas CB) with alternative gases or vacuum circuit breakers (VCB)
- The present webinar will focus on the physical processes relevant to current interruption in HV Gas CB at the zero crossing of the current, i.e. at «current zero» (CZ), using alternative gases as interruption medium.
- The relevant physical processes will be discussed and relevant parameters of SF_6 and alternative gases/mixtures are compared
- Conclusions on the switching performance from such parameter comparison will be drawn and compared to experimental results from literature. Some consequences for the design of HV Gas CB will be discussed.
- This work was prepared within the «gas circle» of the «Current Zero Club» (CZC, http://currentzeroclub.org/) and will be presented by representatives of the organization.

Introduction

Contributors in alphabetical order:

Claessens M. (Hitachi Energy Ltd., Switzerland)

Franck C.M. (ETH Zürich, Switzerland)

Lowke J.J. (CSIRO, Australia)

Robin-Jouan P. (GE, France)

Seeger M. (Hitachi Energy Ltd., Switzerland)

Smeets R.P.P. (KEMA Labs, The Netherlands)

Spencer J. (Univ. Liverpool, United Kingdom)

Tanaka Y. (Kanazawa Univ., Japan)

Uchii T. (Toshiba ESS Corp., Japan)

Yan J. (Univ. Liverpool, United Kingdom)

Part I: Introduction and physical processes

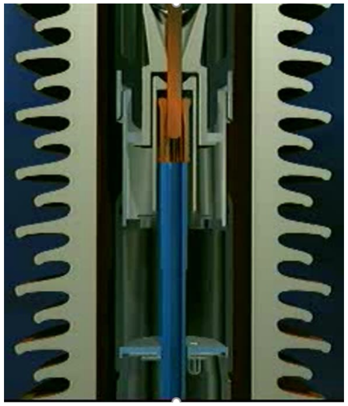
PART 1: Introduction and physical processes

Operation of a high-voltage gas circuit breaker

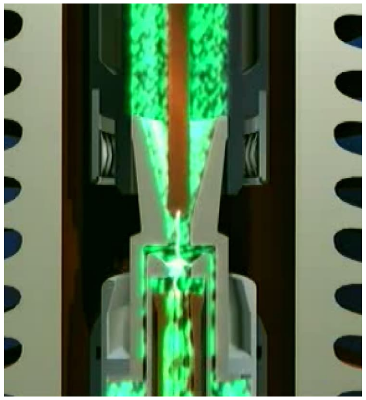
- Two sets of contacts: main contacts and arc contacts
- A mechanical actuator separates the contacts
- High-speed gas flow is generated during the arcing process to remove energy (heat) from the arc column
- A nozzle is used to regulate the flow around the arc column

Aims of circuit breaker design

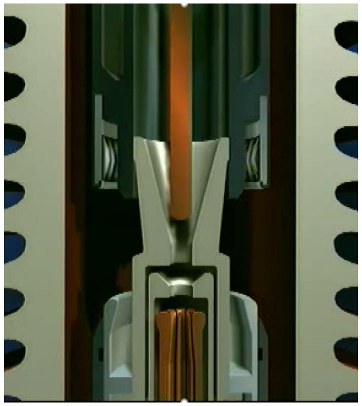
- Creating a gap between the contacts rapidly
- Generating and regulating the gas flow field in an economic and effective manner
- Making the arc a good conductor at high current
- Forcing it to turn into a good insulator after current interruption



Closed

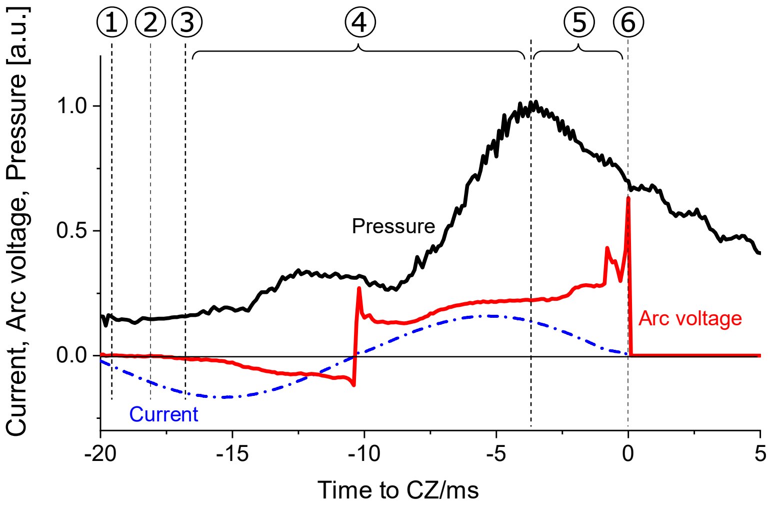


Arcing



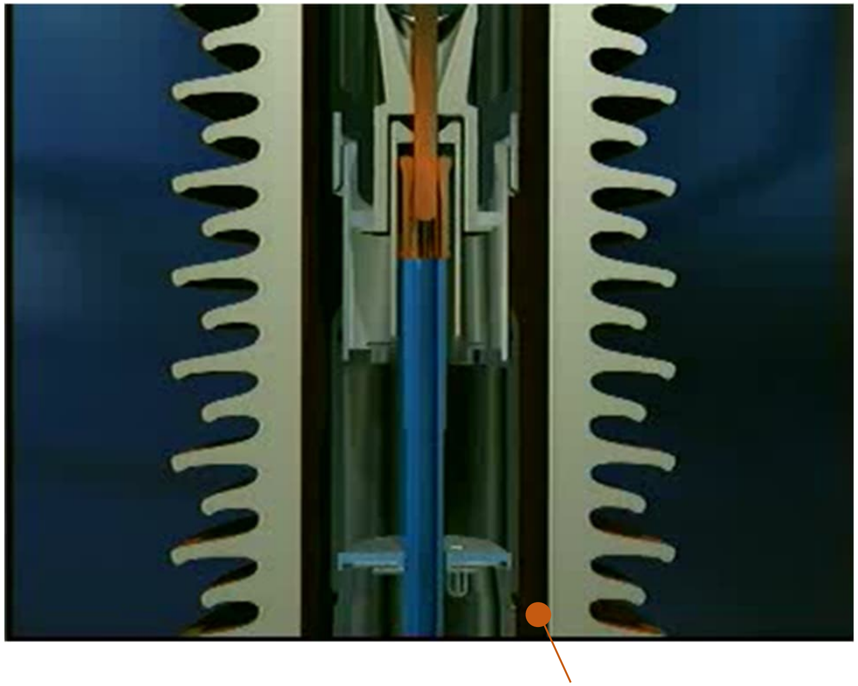
Open

PART 1: Working principle of circuit breakers



① Main contacts start operation.
② Main contacts separate.
(The arcing contacts are still connected.)
③ Arcing contacts separate and arc ignites.
④ Upstream gas is pressurized.
⑤ Gas blasts onto the arc.
⑥ The arc is quenched successfully
at a current zero.

Courtesy of Siemens
<https://www.youtube.com/watch?v=k6spLhEge6I>

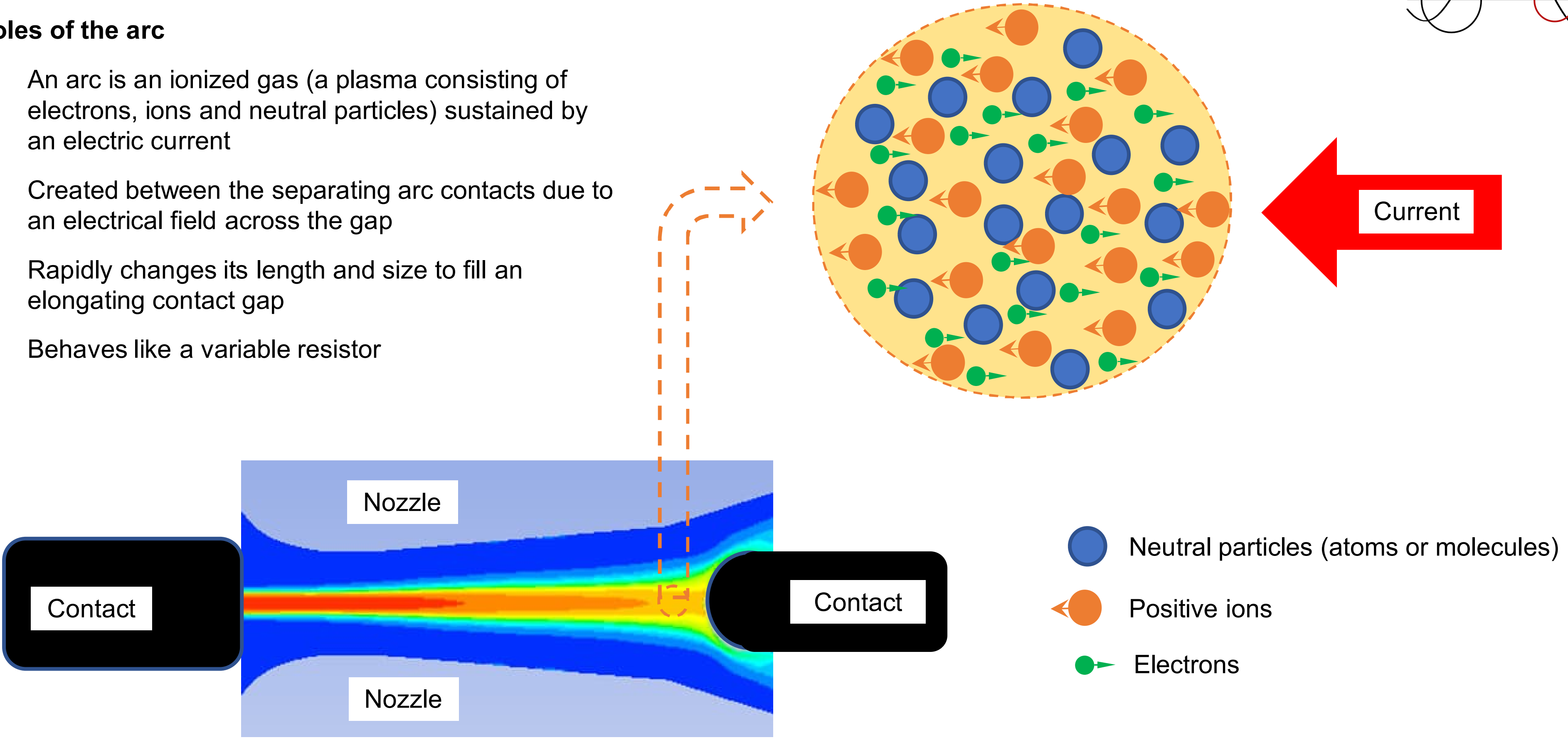


Heating volume

PART 1: Introduction and physical processes

Roles of the arc

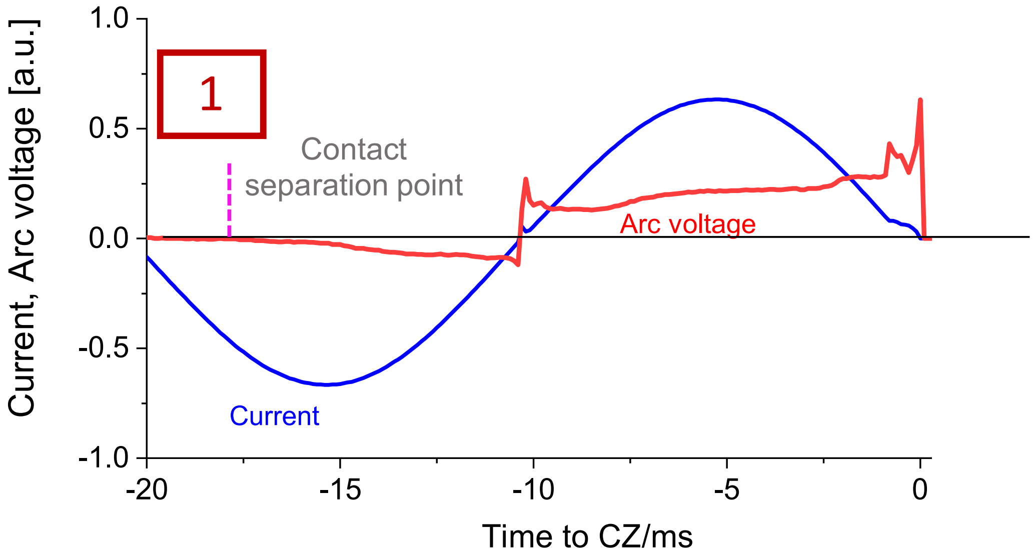
- An arc is an ionized gas (a plasma consisting of electrons, ions and neutral particles) sustained by an electric current
- Created between the separating arc contacts due to an electrical field across the gap
- Rapidly changes its length and size to fill an elongating contact gap
- Behaves like a variable resistor



PART 1: Introduction and physical processes

Sequence of events during the breaking process

1) Fault current passing through closed arc contacts

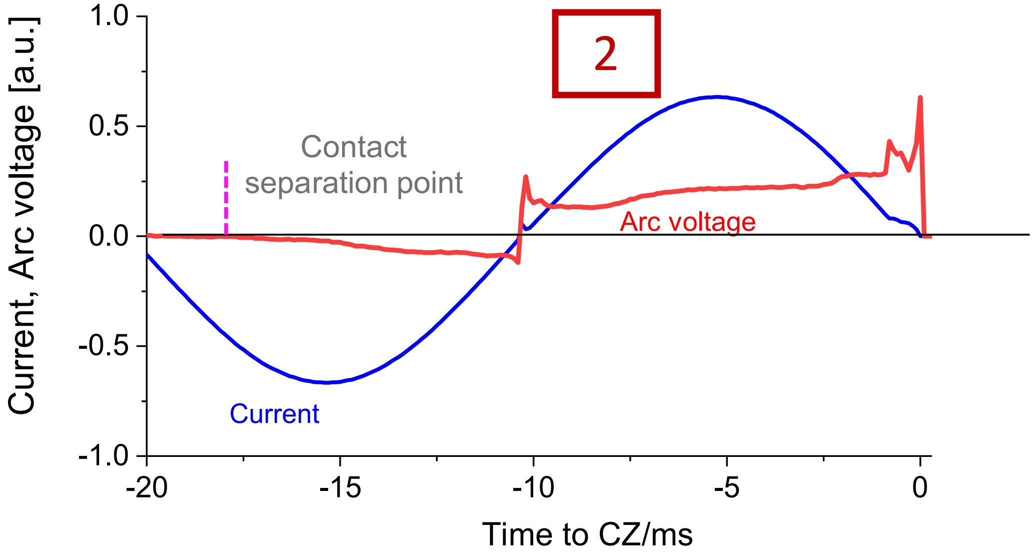


PART 1: Introduction and physical processes

Sequence of events during the breaking process

1) Fault current passing through closed arc contacts
2) Arcing following separation of arc contacts

Heat in arc is removed by gas flow (convection) and radiation

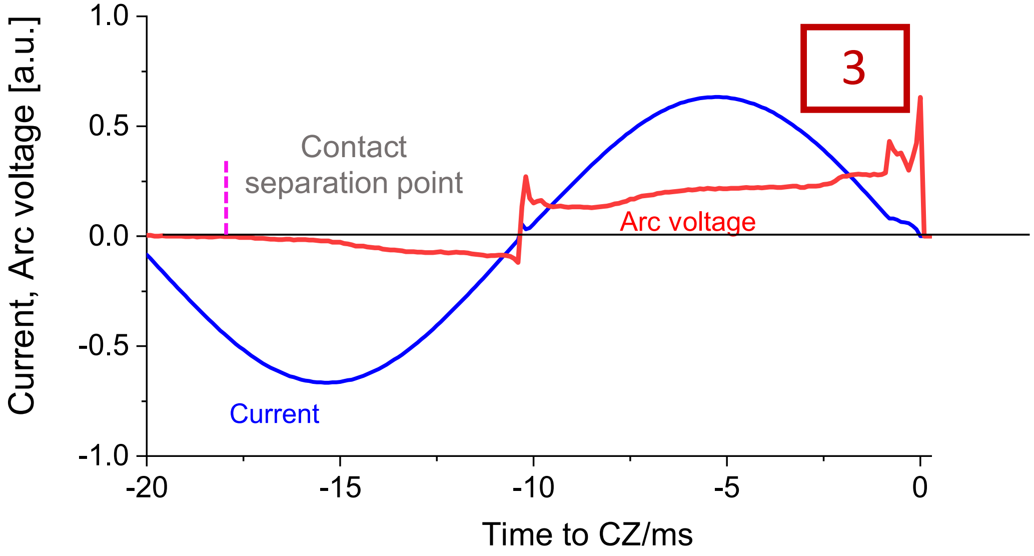


PART 1: Introduction and physical processes

Sequence of events during the breaking process

1) Fault current passing through closed arc contacts
2) Arcing following separation of arc contacts
3) Approaching the final current zero

Arc column shrinks and strong turbulence cools the arc down. Arc voltage rises rapidly.

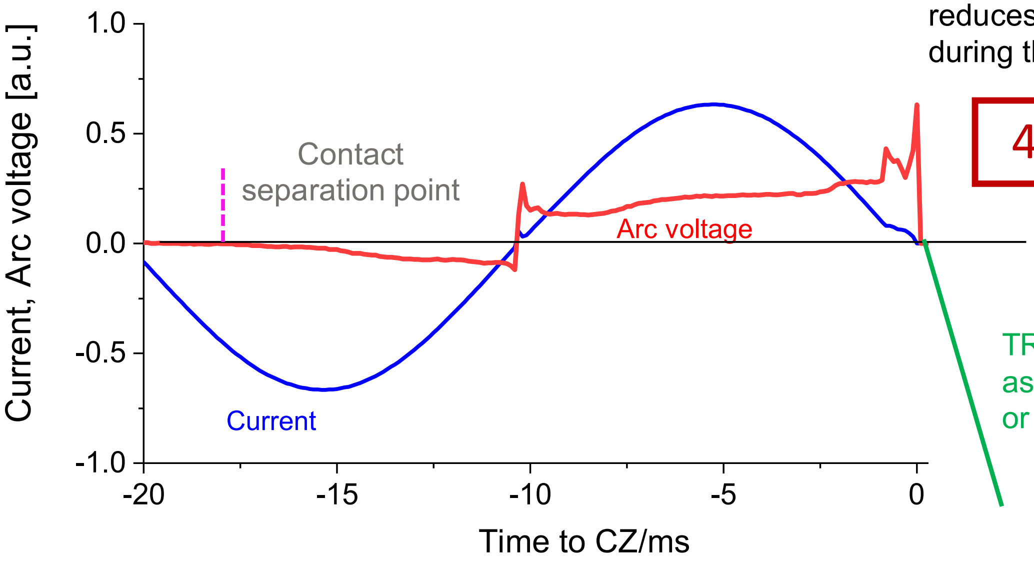


PART 1: Introduction and physical processes

Sequence of events during the breaking process

1) Fault current passing through closed arc contacts
2) Arcing following separation of arc contacts
3) Approaching the final current zero
4) Post arc recovery (100 us)

Hot gas (residual plasma) in contact gap continues to cool down (thermal recovery) and the number of free electrons in it reduces (dielectric recovery) during the stress of TRV.



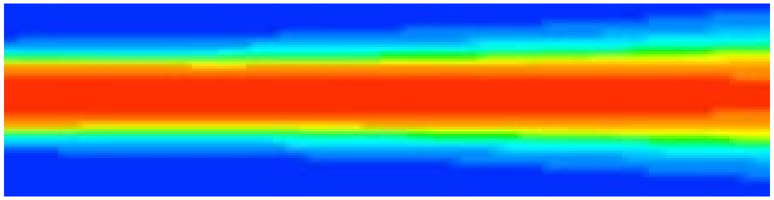
4

TRV rises at a rate of as high as 10 kV/us or more

PART 1: Introduction and physical processes

Variation of arc resistance

- Mainly determined by the temperature (distribution) of the arcing gas
- The physics of mass and heat transfer governs the change of the arc temperature
- Electrical heating (Ohmic heating) increases temperature of gas and reduces the arc resistance
- Cooling (energy removal from arc column) lowers the temperature and leads to higher resistance



Arc resistance is
- dependent on temperature (high temperature leads to low resistivity)
- proportional to length
- Inversely proportional to cross-sectional area

$$R = \rho \frac{l}{A}$$

Rapidly removing heat from the arc (i.e. arc cooling) is key to circuit breaker design.

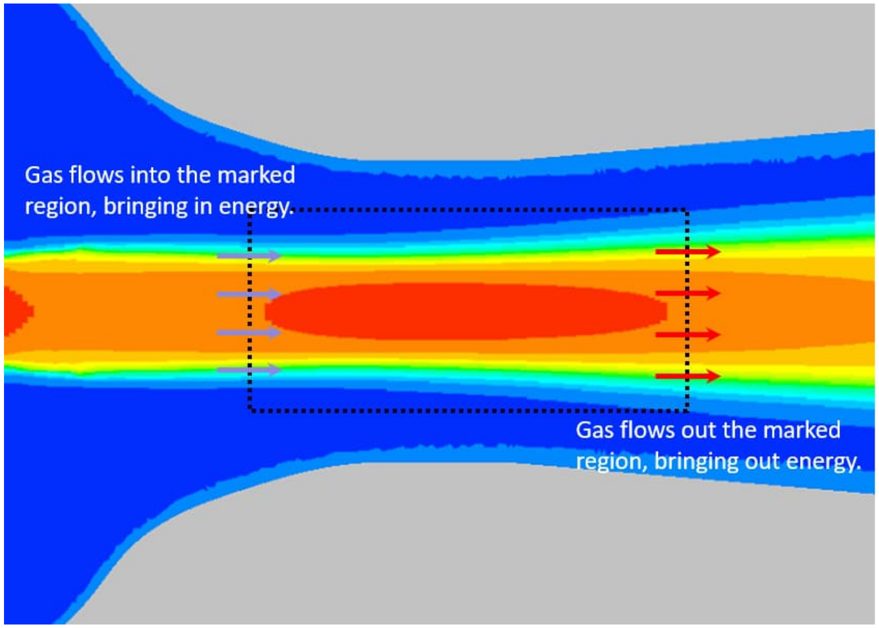
PART 1: Introduction and physical processes

Physical mechanisms: Convection

The design of modern high-voltage gas circuit breakers is based on the principle of gas blast

- Gas blast means the generation and use of high-speed gas flow for arc control
- **Convection**: When a fluid (such as a gas) flows, its mass together with the thermal energy (heat) stored in it moves in space, realizing energy transfer

  ~ Density * Velocity * Energy per unit mass
- Example: blowing out a candle



Convection plays an important role in high current arcs where the arc column has a relatively large diameter

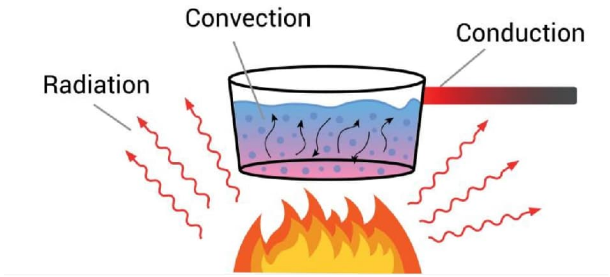
PART 1: Introduction and physical processes

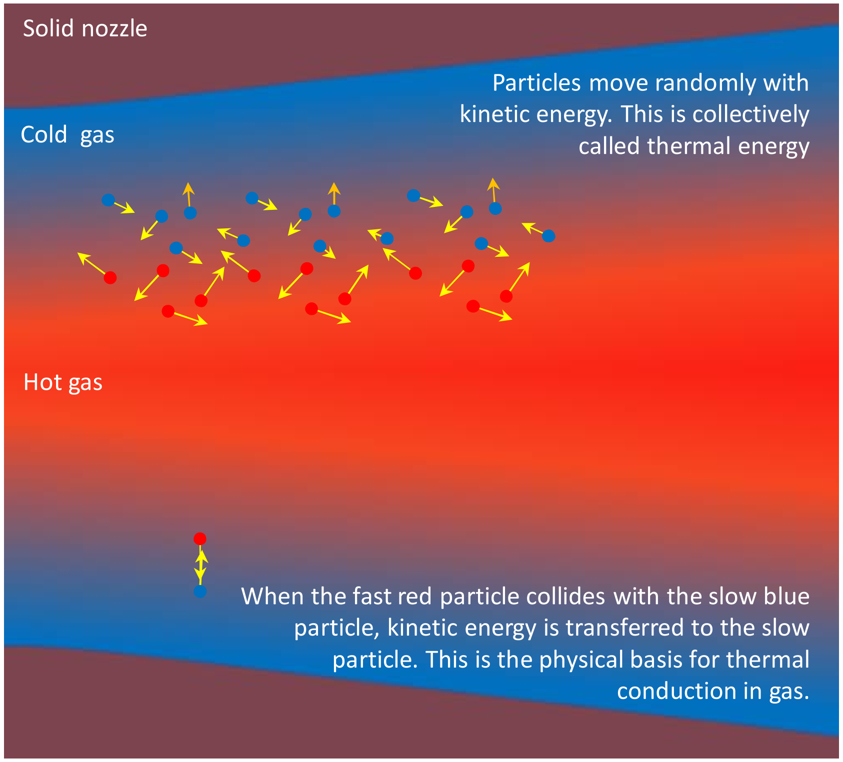
Physical mechanisms: Thermal conduction

- Transfer of heat in gas, liquid and solid
- The medium does not need to move macroscopically
- Through collisions of randomly moving particles (atoms, molecules, electrons and ions)
- Conduction is proportional to temperature difference (gradient)
- The ability is defined by its thermal conductivity

~Thermal conductivity * Gradient of temperature

- Example: A metal bar conducts heat from a fire cooling the fire





Particles move randomly with kinetic energy. This is collectively called thermal energy

When the fast red particle collides with the slow blue particle, kinetic energy is transferred to the slow particle. This is the physical basis for thermal conduction in gas.

Thermal conduction becomes important when gas is not moving or moving slowly in direction of temperature gradient

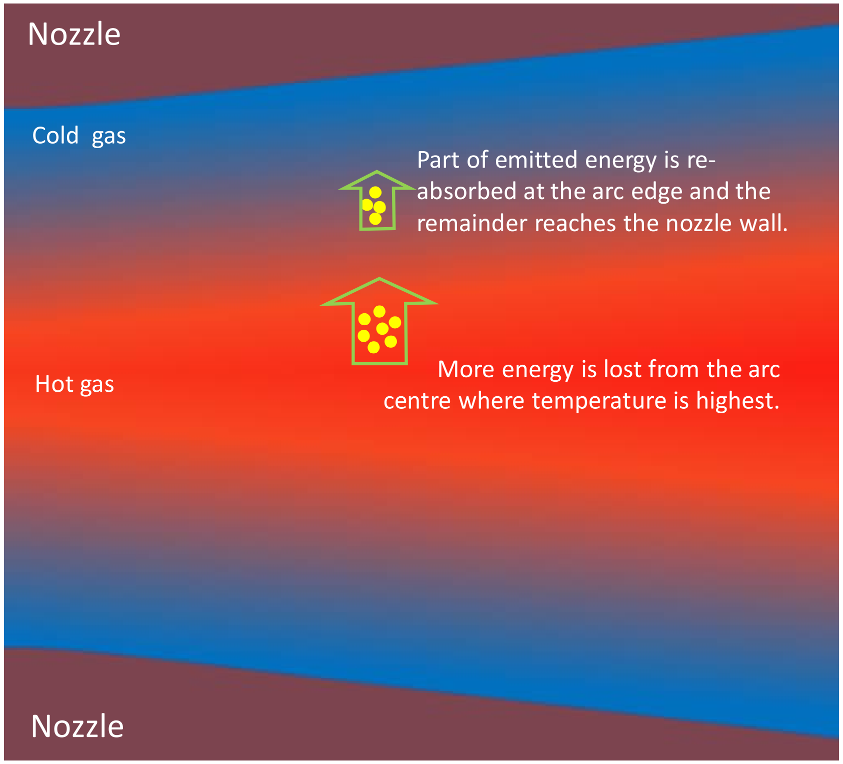
PART 1: Introduction and physical processes

Physical mechanisms: Radiation

- Electromagnetic wave in nature but can also be interpreted using the concept of photons
- Photons at different wavelengths or frequencies
- Some photons get absorbed when travelling in the gas, so gas is "optically thick" (less transparent) to them
- Some photons escape from the arc. This is why we can see an arc.
- Radiation transfer takes place in all directions

Sun: ~ 6,000K

Arc: ~ 20,000K



Nozzle

Cold gas

Part of emitted energy is re-absorbed at the arc edge and the remainder reaches the nozzle wall.

Hot gas

More energy is lost from the arc centre where temperature is highest.

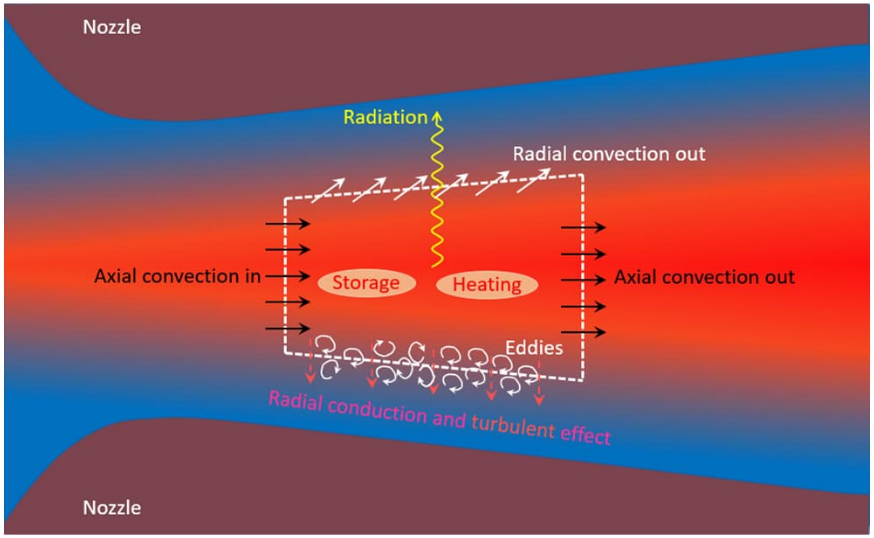
Nozzle

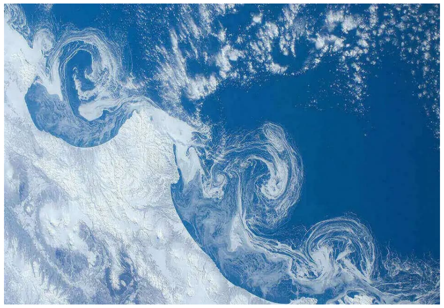
Radiation transfer is an important mechanism for energy transfer in arcs

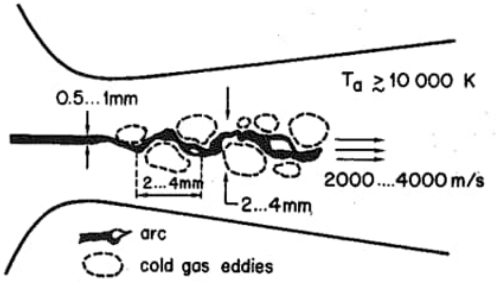
PART 1: Introduction and physical processes

Physical mechanisms: Turbulence

- Develops in unstable flows (in contrast to laminar flows)
- Turbulence eddies (3D) of different sizes
- Eddies continuously generated and destroyed
- Rotation of eddies enhances mixing of hot and cold gases
- Most effective in removing heat from a thin arc column (diagram below)
- A dominant arc cooling mechanisms at current zero period
- Very challenging to model







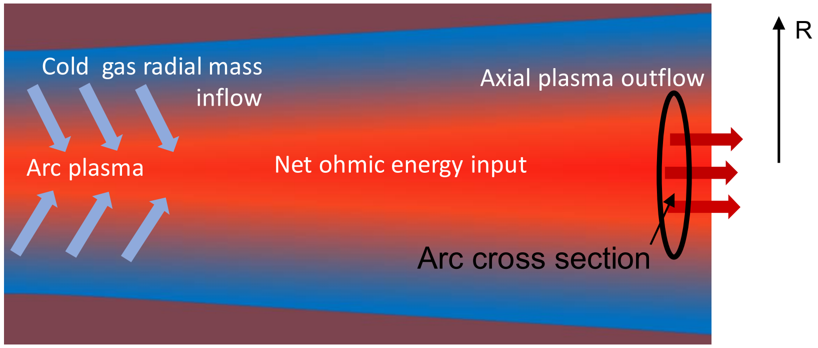
Source of ocean eddies: https://cosmosmagazine.com/earth/oceans/energetic-ocean-eddies-on-the-rise/
Source for nozzle turbulence: Ragaller K. (ed.), Current Interruption in HV Networks, New York, NY: Plenum Press, 1978 [ISBN 0-306-40007-3]

Turbulence is determined by 3D processes. It is the main cooling process near current zero

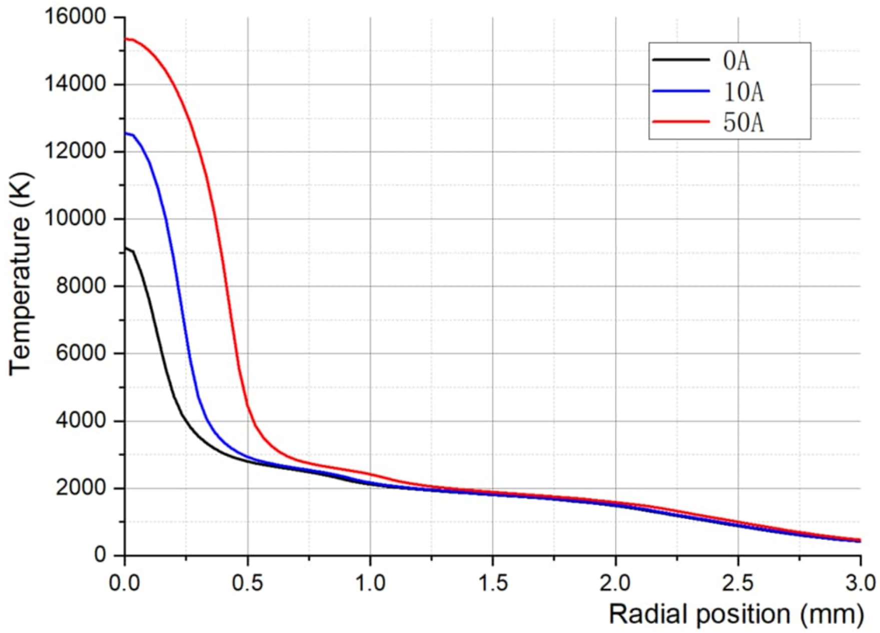
PART 1: Arc thermal cooling

Radial temperature profile and arc column size

- Energy loss by convection and radiation are decisive for the radius of the high current arc



- Approaching current zero, the arc radius reduces and at CZ a hot plasma column is remaining
- Among radiation, convection, conduction and turbulent cooling, turbulence is the dominant energy removal mechanism approaching current zero
- This is determined by thermodynamic parameters



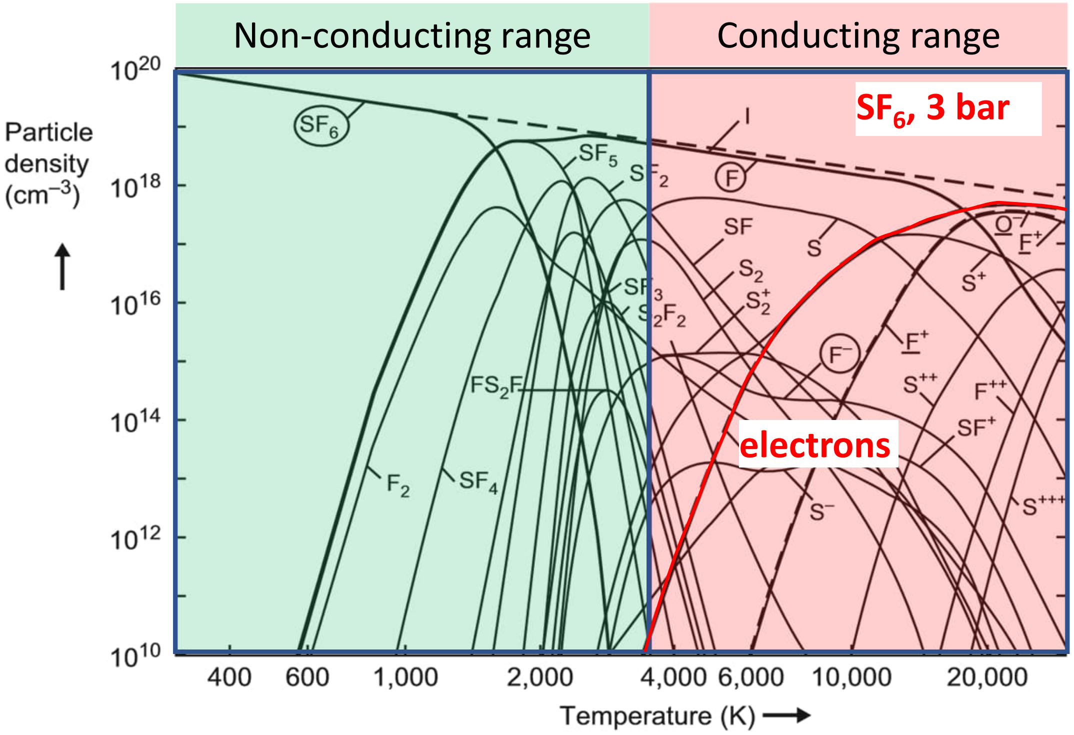
Radial temperature profile decreases with current

Thermodynamic parameters, radiation and turbulence are important for the radial arc temperature profile

PART 1: Composition of the plasma

Composition varies with temperature and pressure

- Plasma decomposes into many species
- This process is defined by temperature, pressure and initial concentration of gas components
- At high temperatures above 10000 K the plasma consists mainly of atoms, ions and electrons
- When plasma cools down molecules are formed
- Reactions occur on finite time scale leading to deviations from chemical equilibrium



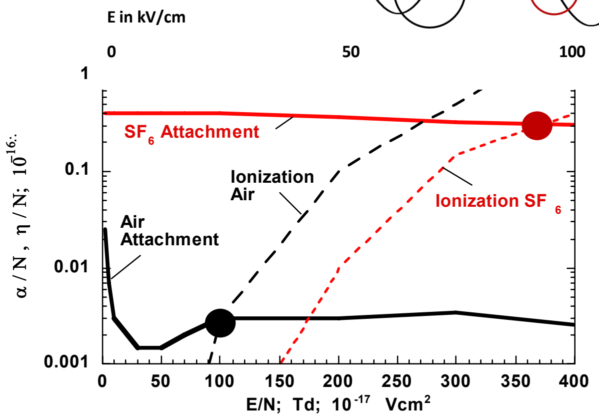
Hugh M Ryan (Ed.), High Voltage Engineering and Testing (3rd Edition), IET Publications, 2013[978-1849192637]

The composition of the plasma for given gas mixture depends on pressure, temperature and time scale

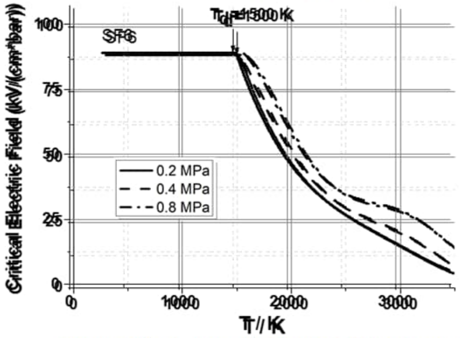
PART 1: Electron attachment

Plasma Processes influence electron removal or enhancement and thus arc conductance near “current zero”. Knowledge of them may be important in selecting alternative gases.

- Electron diffusion: Electrons can diffuse out of a narrow arc channel and be attached in the surrounding gas leading to an increase of arc resistance.
- Electron attachment: Electrons in SF_6 and alternative gases can attach to molecules, forming negative ions. These have conductivities of only about 1% of electrons.
- Ionization and electron attachment coefficients have been measured for common gases. Results for SF_6 and air show that attachment in SF_6 is more than an order of magnitude higher than for air.
- Critical electric fields: High fields applied after current zero can produce electric breakdown. This is described by the critical electric field which is decisive for the dielectric recovery. At the critical field electron attachment equals ionisation, i.e. net ionisation is zero.



J. J. Lowke, *J. Phys. D:Appl. Phys.* **52** (2019) 464001



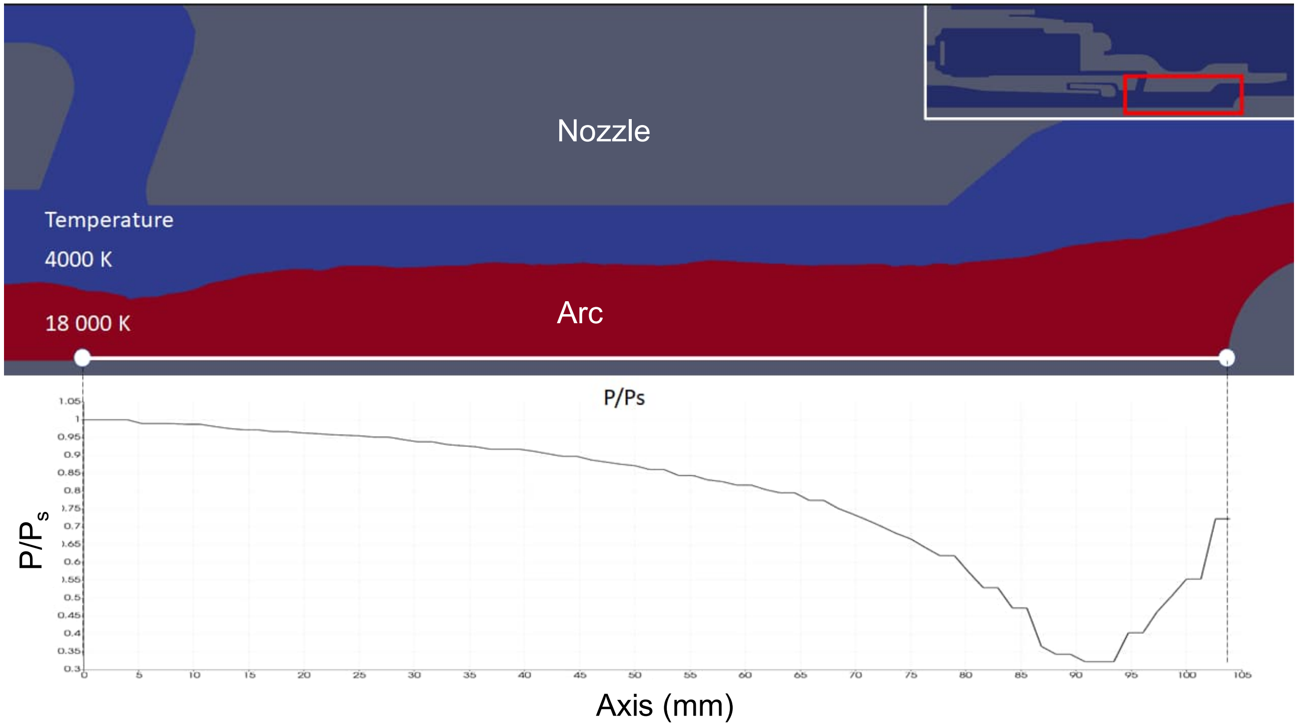
Seeger, M.; Niemeyer, L.; Bujotzek, M. Leader propagation in uniform background fields in SF_6. J. Phys. D Appl. Phys. 2009, 42

Electron attachment might play a role for thermal interruption and is decisive for the dielectric recovery

PART 1: Arc zone geometry influence

Influence of axial pressure profile in the arc zone

- The axial pressure profile in the arc zone influences the arc radius and gas/plasma acceleration
- In the nozzle throat the speed of sound is reached
- Onset of turbulence is due to shear flow at the arc boundary
- Widening of arc downstream of nozzle throat
- Most effective arc cooling is in the region of the throat and downstream region
- High pressure and acceleration leads to small arc cross section with high convective and turbulent cooling



Courtesy GE Renewable Energy

The arc zone geometry is an important design parameter for the performance

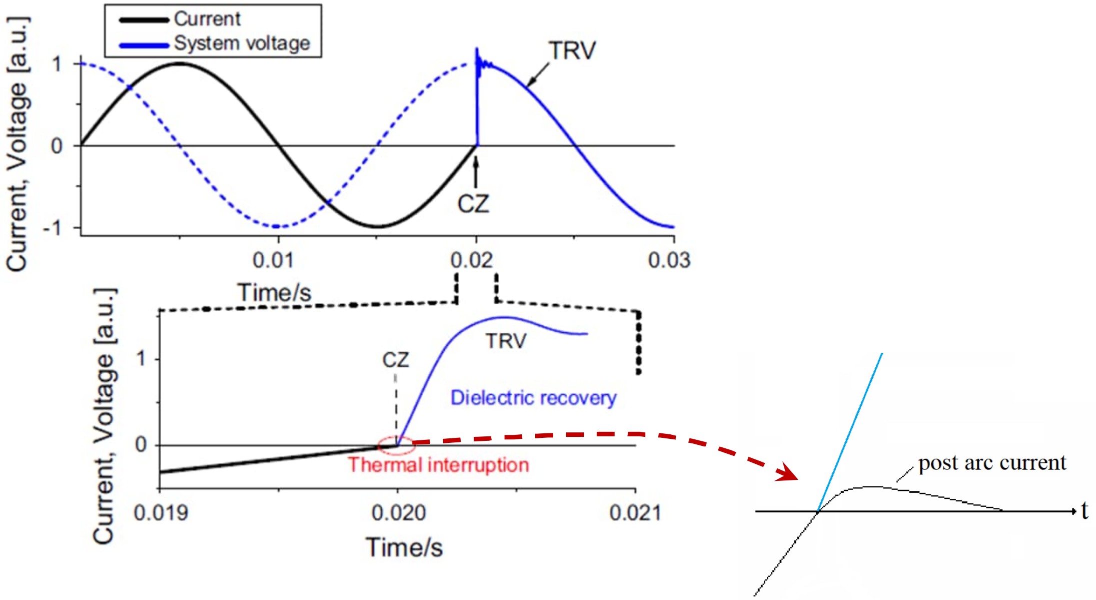
PART 1: Thermal interruption

Thermal recovery

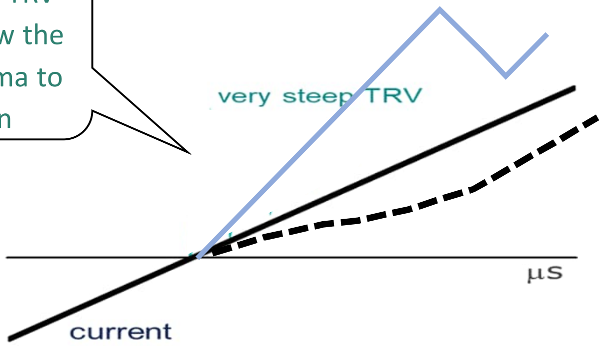
- After CZ, the resistance of the arc channel increases
- Thermal interruption occurs if the power input (defined by post-arc current (PAC) and applied TRV) is less than the cooling power, leading to a decrease of PAC

Thermal re-ignition

- Decision within a few microseconds
- Slow breakdown (several µs)



Steepness of TRV does not allow the residual plasma to cool down

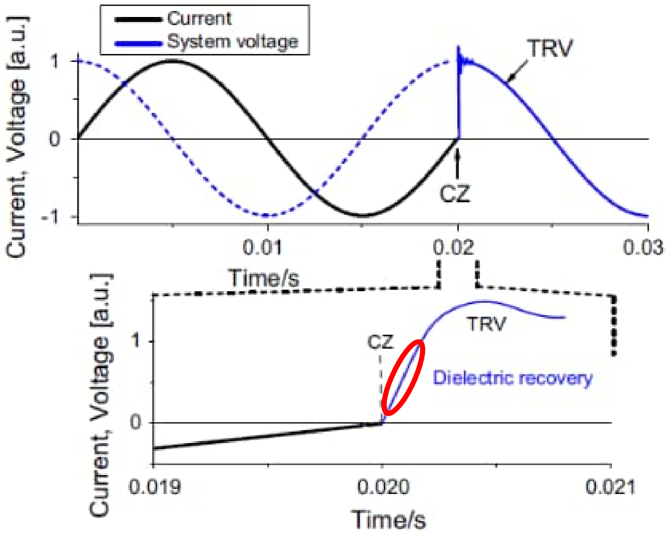


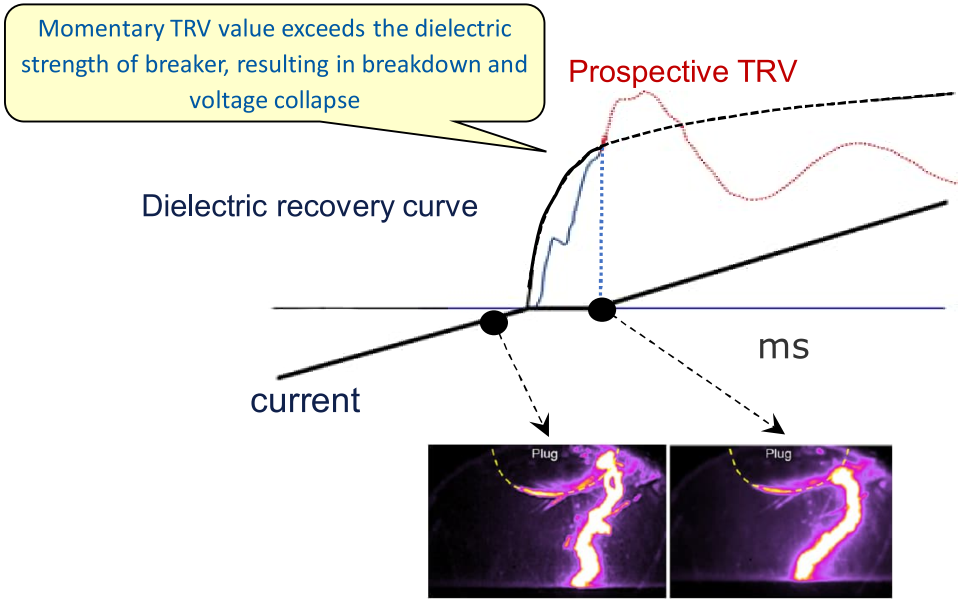
Thermal re-ignition occurs in the residual arc channel, very shortly after CZ

PART 1: Dielectric recovery

Early dielectric recovery

- Breakdown is of “dielectric” nature, i.e., electron avalanche processes in contrast to thermal runaway. Characterized by fast breakdown (order of 10 ns)
- Breakdown in the arc channel below 100 µs after CZ, typically




Momentary TRV value exceeds the dielectric strength of breaker, resulting in breakdown and voltage collapse

Arc 30 µs before CZ

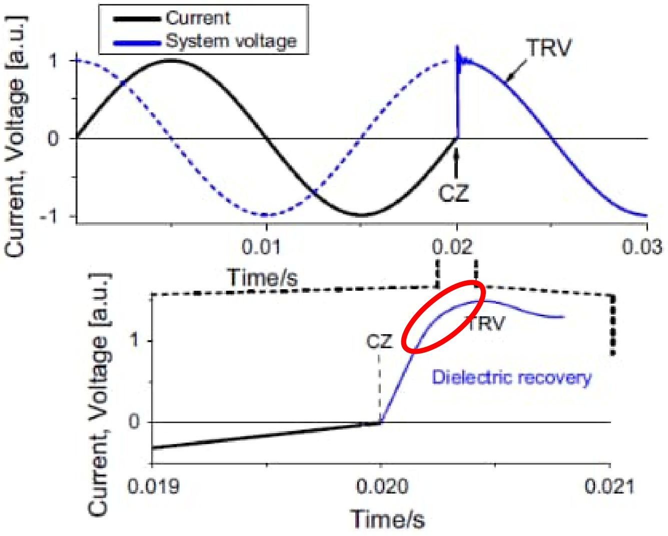
Breakdown 31 µs after CZ

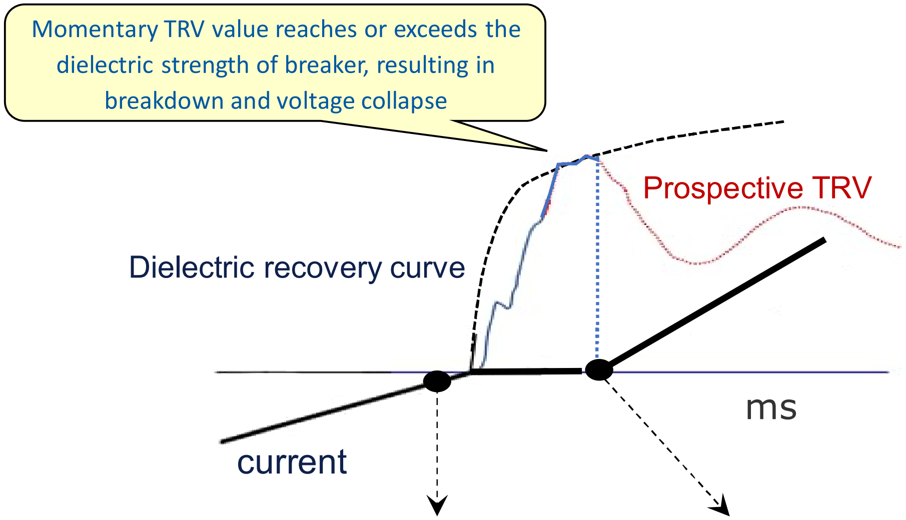
Early dielectric recovery occurs inside the residual plasma column

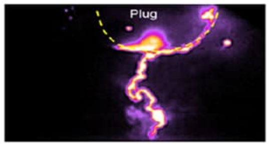
PART 1: Dielectric recovery

Late dielectric recovery

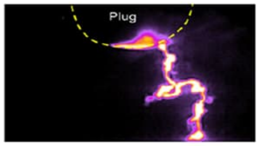
- Breakdown is of “dielectric” nature, i.e., electron avalanche processes in contrast to thermal runaway. Characterized by fast breakdown (order of 10 ns)
- Breakdown outside the arc channel, above 100 μs after CZ, typically




Momentary TRV value reaches or exceeds the dielectric strength of breaker, resulting in breakdown and voltage collapse



Arc 30 μs before CZ



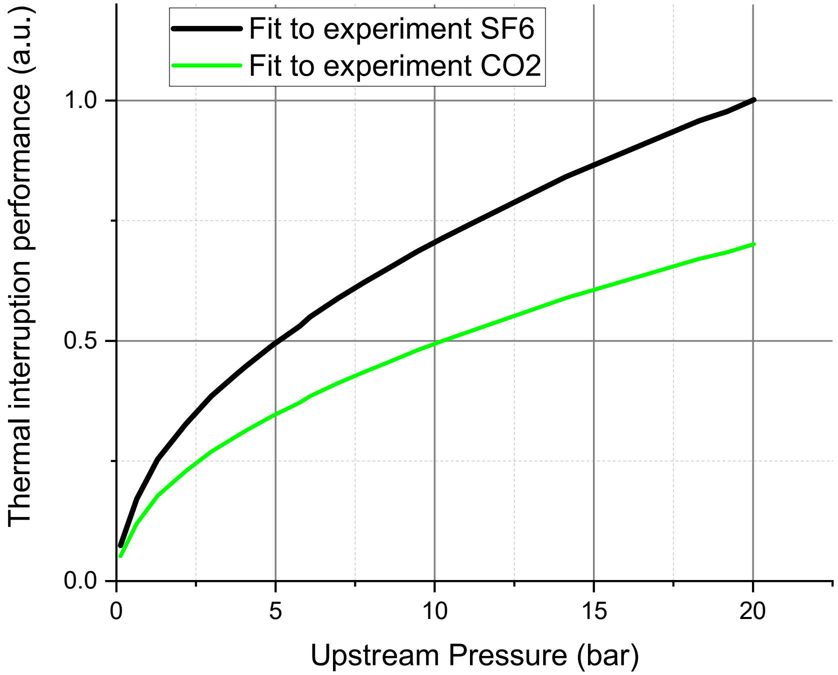
Breakdown 202 μs after CZ

Late dielectric recovery occurs outside the residual plasma column

PART 1: Pressure influence of Thermal Interruption

Influence of upstream pressure in axially blown arcs

- The thermal interruption performance increases with about the square-root of the upstream pressure
- This is due to decreasing arc diameter with increasing pressure, turbulent cooling (thinner arc is easier to cool) and pressure dependence of the material properties
- Shown in numerous experiments with various gases and by theory
- Helps to benchmark different gases

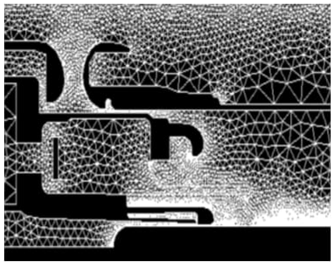


The thermal interruption performance increases with the square-root of the applied upstream pressure

PART 1: Simulations

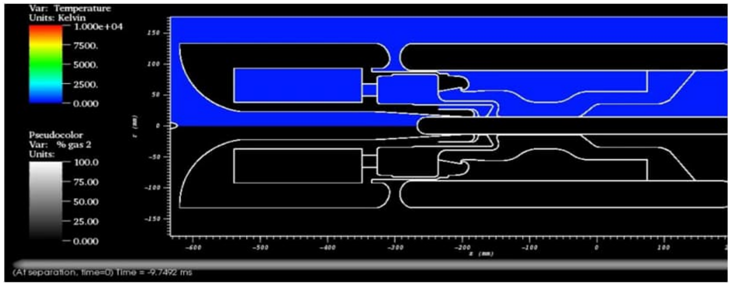
Numerical tools

- 0D Macroscopic tools (no discretisation of the circuit breaker geometry)
- 2D axisymmetric and 3D tools
- In-house developments and commercial solutions (ANSYS, COMSOL, …)



Validations

- Validation through dedicated test devices: overpressure, temperature (spectroscopy), erosion, radiative flux, arc voltage, post arc current, optical diagnostics for visualisation of density variations, electron density etc
- Validation through circuit breaker test results: overpressure, arc voltage, erosion, post arc current



Courtesy GE Renewable Energy

Reliability

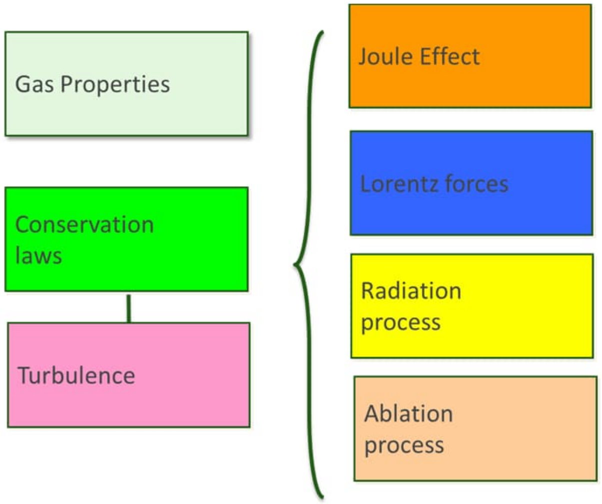
- Possibility to build criteria for design studies (for thermal and dielectric interruptions)
- Good agreement between measurement and simulation results
- Relatively good agreement for breaking prediction (depending on the test duties)

Numerical simulations can be used for circuit breaker design studies with high reliability

PART 1: Simulations

General aspects

- Numerical simulation tools are essential to increase our arc physics knowledge
- Allow fundamental analysis, test result explanation and test reduction
- Developments during the last 20 years allow for industrial applications



Gas Properties

Conservation laws

Turbulence

Joule Effect

Lorentz forces

Radiation process

Ablation process

Fundamentals

Fundamental continuity relationships for the gas are solved using finite element or volume methods

What has to be considered:

- Maxwell equations defining electric and magnetic fields
- Joule effect and Lorentz forces
- Radiation process (emission and absorption in the gas)
- Wall erosion modelling (insulating parts and electric contacts)
- Ionization considered via physical property variations
- Turbulence (fundamental work to be done)
- Deviations from thermal and chemical equilibrium

Fundamental fluid mechanics equations are successfully used to simulate arcs in CB

PART 1: Non-LTE influence

- Current interruption= Sufficient reduction of **electrical conductance** between electrodes
- **TE (Thermodynamic Equilibrium)**

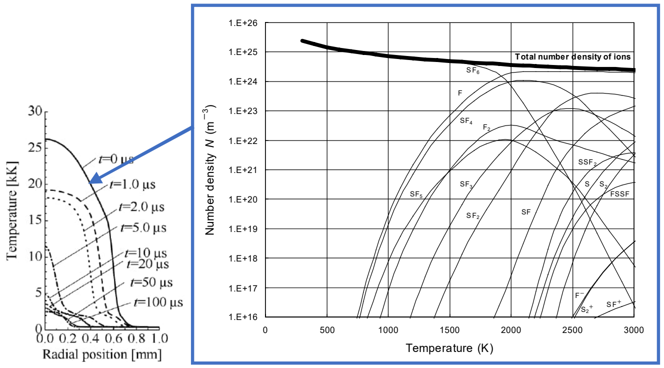
  Composition in a plasma is uniquely determined by temperature

  ➔ All thermodynamic and electrical properties (e.g. electrical conductance) are uniquely determined by temperature
- **LTE (Local Thermodynamic Equilibrium)**

  Temperature is distributed, and TE can be assumed at each local point
- **Non-LTE**

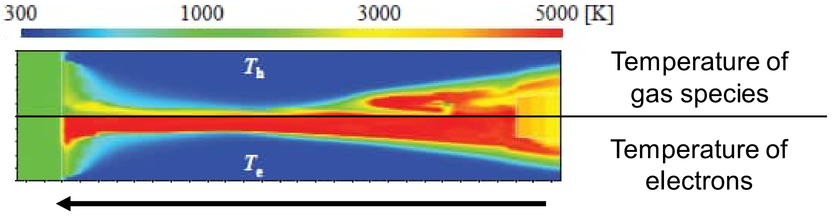
  (1) *Chemically non-equilibrium*: Composition in plasma NOT uniquely determined by temperature, typically when process time scale is significantly shorter than chemical reaction time

  (2) *Thermally non-equilibrium*: Temperatures of electrons and gas species are different, typically when very fast transient electrical field is applied to the plasma



LTE concept

K. P. Brand, J. Kopainsky, 'Particle Densities in a Decaying SF$_6$ Plasma', J. Appl. Phys., vol. 16, pp. 425-432, 1978



Temperature of gas species

Temperature of electrons

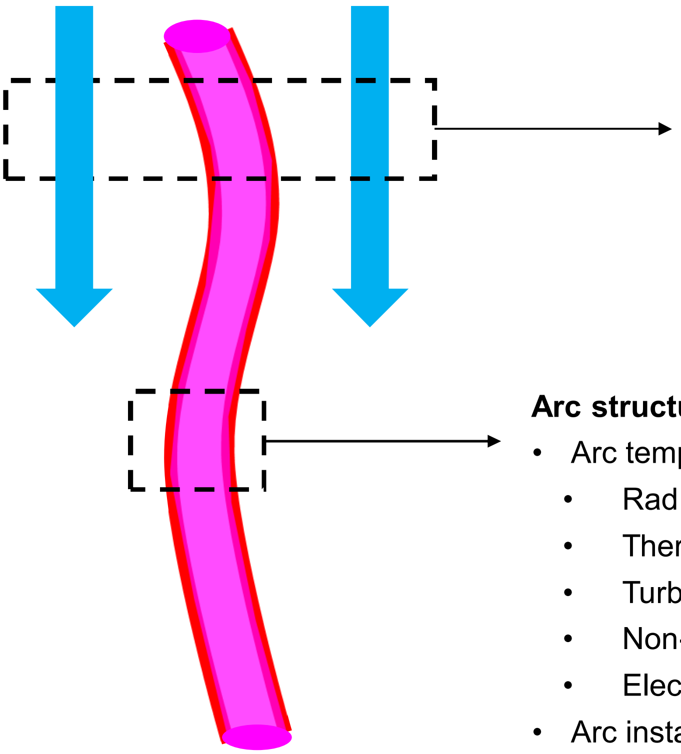
Electrical field

Non-LTE simulation

Y. Tanaka, T. Iijima, 'Hybrid Thermofluid Modeling with LTE and non-LTE Assumption for Decaying Molecular Gas Arcs', Int. Conf. on Electric Power Equipment-Switching Technology(ICEPE-ST 2022), pp. 93-98, 2022

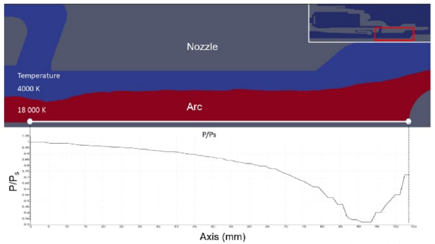
Deviations from equilibrium are important for prediction of interruption performance

PART 1: Summary of influencing parameters



External parameters (defined by design)

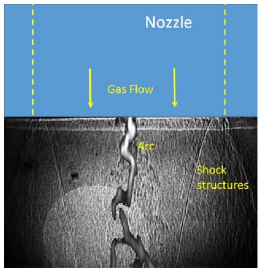
- Imposed axial pressure profile
- Blow gas pressure and temperature
- Gas composition and filling pressure
- Contact separation velocity
- Nozzle material

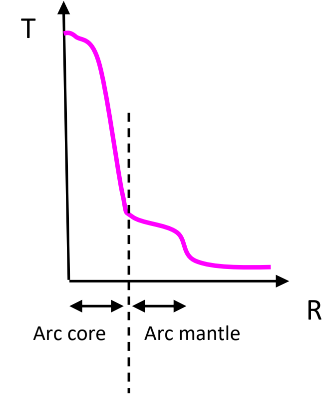


Courtesy GE Renewable Energy

Arc structure at CZ (defined by material properties)

- Arc temperature profile → strongly influenced by material properties
  - Radiation transport
  - Thermophysical and transport properties
  - Turbulence
  - Non-equilibrium (chemical and temperature)
  - Electrical conductivity distribution
- Arc instabilities leading to variations in shape

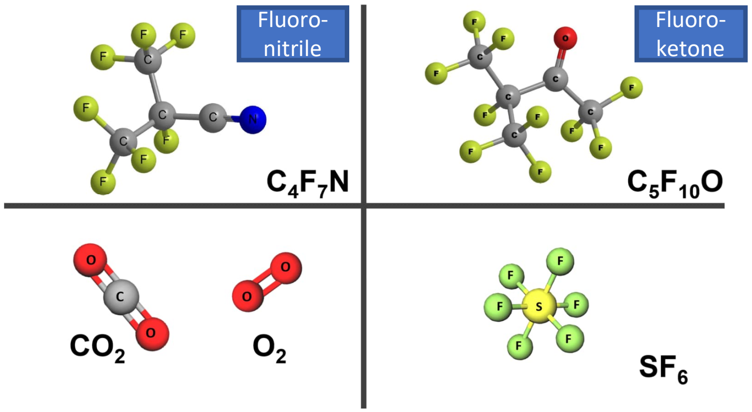




Part II: Comparison of properties for SF_6 alternative gases

PART II: Properties of gases and mixtures

Gases of interest



Abbreviations:
C4-FN= C_4F_7N
C5-FK = $C_5F_{10}O$
GWP = Global warming potential

Pure gases

	CAS number	Molec. weight (g/mol)	Density (kg/m3) at 0.1 MPa	Boiling point/ °C	GWP (100yr)	ODP	Flammability	Toxicity LC50 (4h) ppmv	Toxicity TWA ppmv	Electric strength/ p.u. at 0.1 MPa
SF_6	2551-62-4	146	6.17	-64	25200*	0	No	> 5e5	1e3	1
CO_2	124-38-9	44	1.98	-78.5	1	0	No	> 3e5	5e3	≈ 0.3
C5-FK	756-12-7	266	10.7	26.9	< 1	0	No	≈2e4	225	≈ 2
C4-FN	42532-60-5	195	7.9	-4.7	2100**	0	No	12e3…15e3	65	≈ 2

Gas mixtures for switchgear

	C_{ad} % molar	p_{min}/ MPa	T_{min}/°C	GWP (100y)	D.S.	Toxicity LC50 ppmv
SF_6	-	0.43…0.6	-41…-31	25200	0.86…1	-
CO_2	-	0.6…1	≤ -48	1	0.4…0.7	> 3e5
CO_2/C5-FK/O_2	≈ 6…12	0.7	-5…+5	1	≈ 0.75…0.86	> 2e5
CO_2/C4-FN and CO_2/C4-FN/O_2	≈ 3.5…6	0.7…0.8	-30…-10	293…690	≈ 0.87…0.96	> 1e5

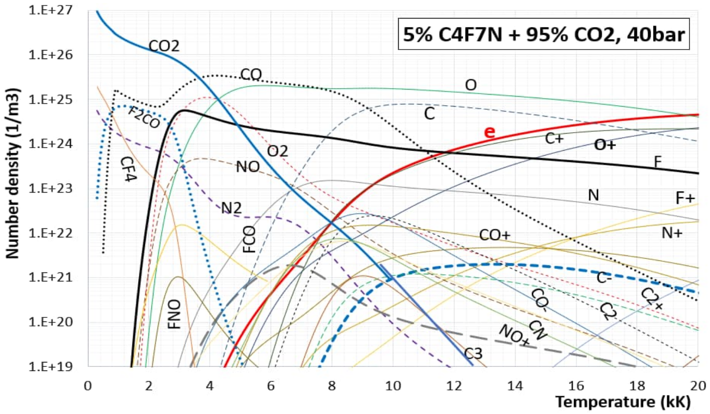
* IPCC6: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf
** https://multimedia.3m.com/mws/media/1132124O/3m-novec-4710-insulating-gas-tech-data-sheet.pdf

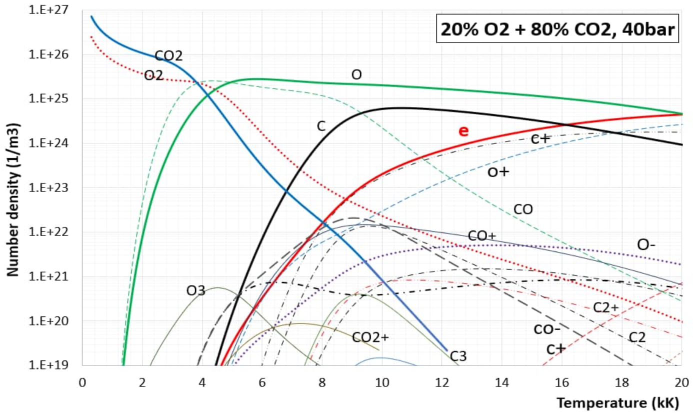
Important properties: boiling point, electric strength, GWP, Ozone layer Depletion Potential and toxicity

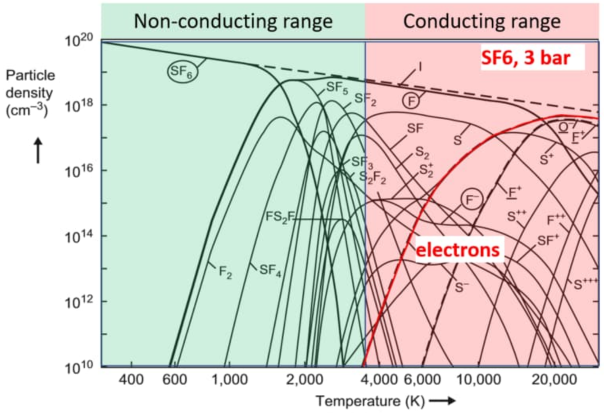
PART II: Composition

Composition calculations of different gas mixtures

- At cooling down C_4F_7N does not completely recombine into its original molar concentration once thermally dissociated
- This is different from SF_6
- Composition defines the material parameters (thermodynamic, transport, radiation etc)
- C_4F_7N mixtures more complex compared to CO_2/O_2, similar to SF_6







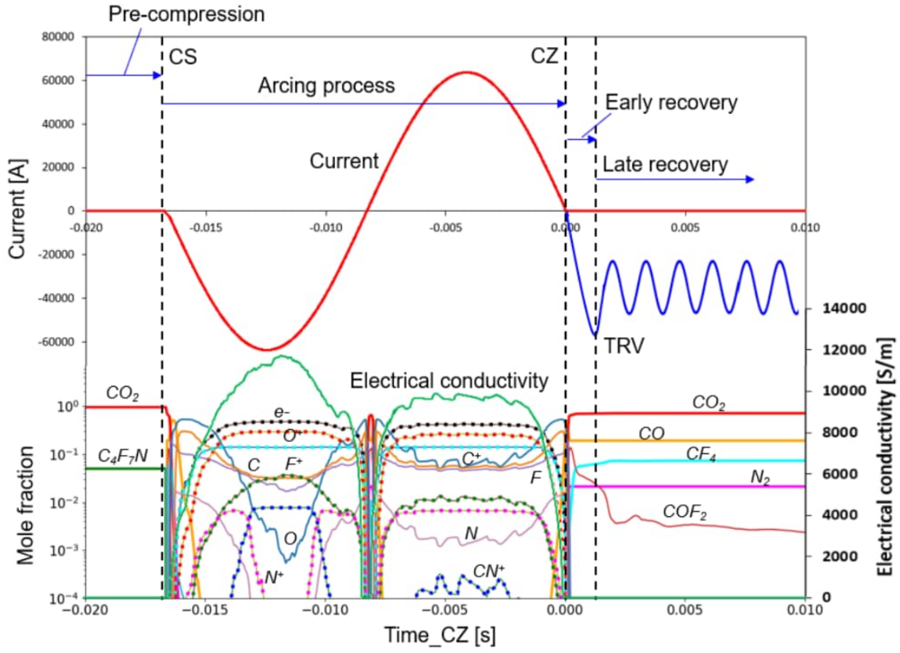
The composition of the plasma and hot gas is decisive for the interruption performance

PART II: Composition in various phases

Composition in the arc at various phases

- Composition varies over the arcing and interruption phases (here shown for LTE)
- Different for the different gases and mixtures
- Non-chemical equilibrium needs to be considered: e.g. the time it takes for C_4F_7N to be dissociated is close to 0.1 ms at 2000 K, while at 1500 K, the value is about 5 s from calculations [1]
- Not only temperature and pressure but also time will be of importance

Note: In the non-arced region C_4F_7N remains unaffected



---

[1] Chen L, Zhang B, Xiong J, Li X, and Murphy A B, "Decomposition mechanism and kinetics of iso-C4 perfluoronitrile (C_4F_7N) plasmas", J. Appl. Phys. 126, 163303 (2019); https://doi.org/10.1063/1.5109131

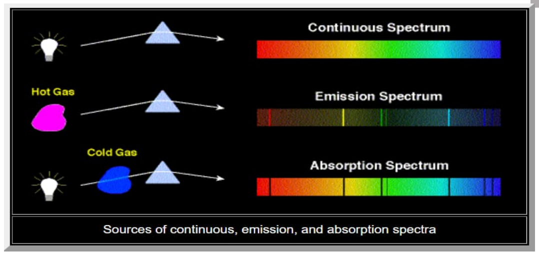
J. D. Mantilla, X. Ye, T. H. Song, Y. Park, S. Brynda, and H. Sohn, 'Theoretical and Practical Behaviour of Eco-friendly SF_6 Alternativesin High Voltage Switchgear', CIGRE Sess. 48, 2020

The composition of the plasma and hot gas is decisive for the interruption performance

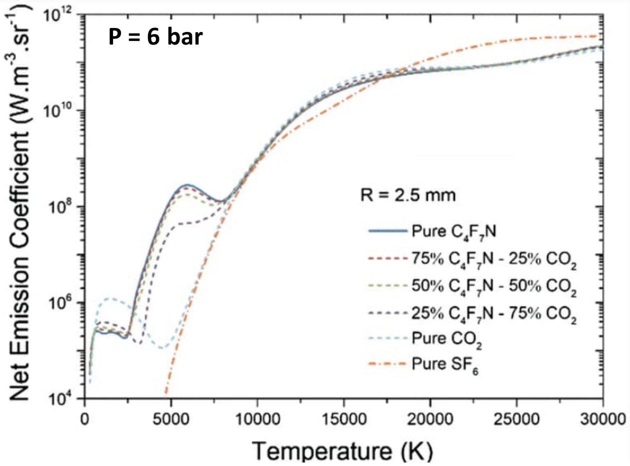
PART II: Radiation

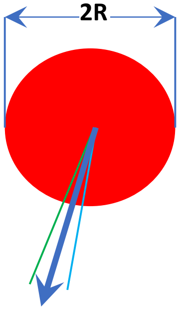
Radiation as an energy transfer mechanism

- Emitted radiation is absorbed by the medium it passes through
- Differences between SF_6 and C4-FN are in the discrete emission and absorption of the different species (atomic and molecular excitations)
- Continuous absorption is at similar level in SF_6 and CO_2 based mixtures
- Consequence is a different energy transfer through the arc
- Affects the arc temperature profile and the energy leaving the arc



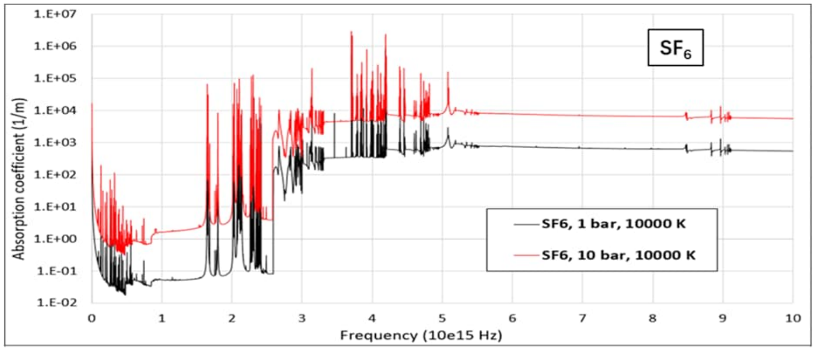
Sources of continuous, emission, and absorption spectra



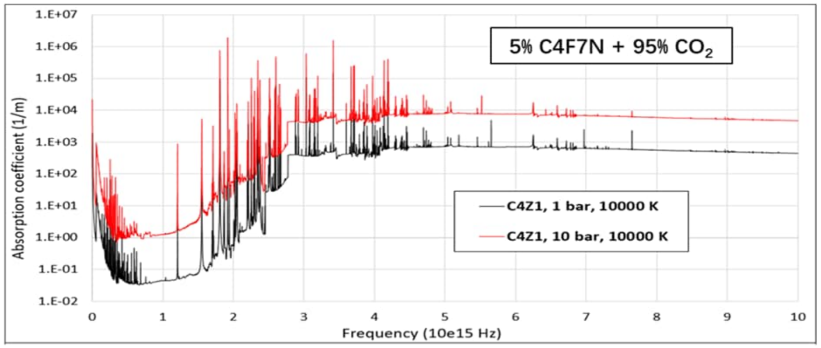


Net emission from centre of sphere

SF_6



$5\%\ C_4F_7N + 95\%\ CO_2$



Radiation spectra are complex. The differences lead to changes in energy transport through the arc

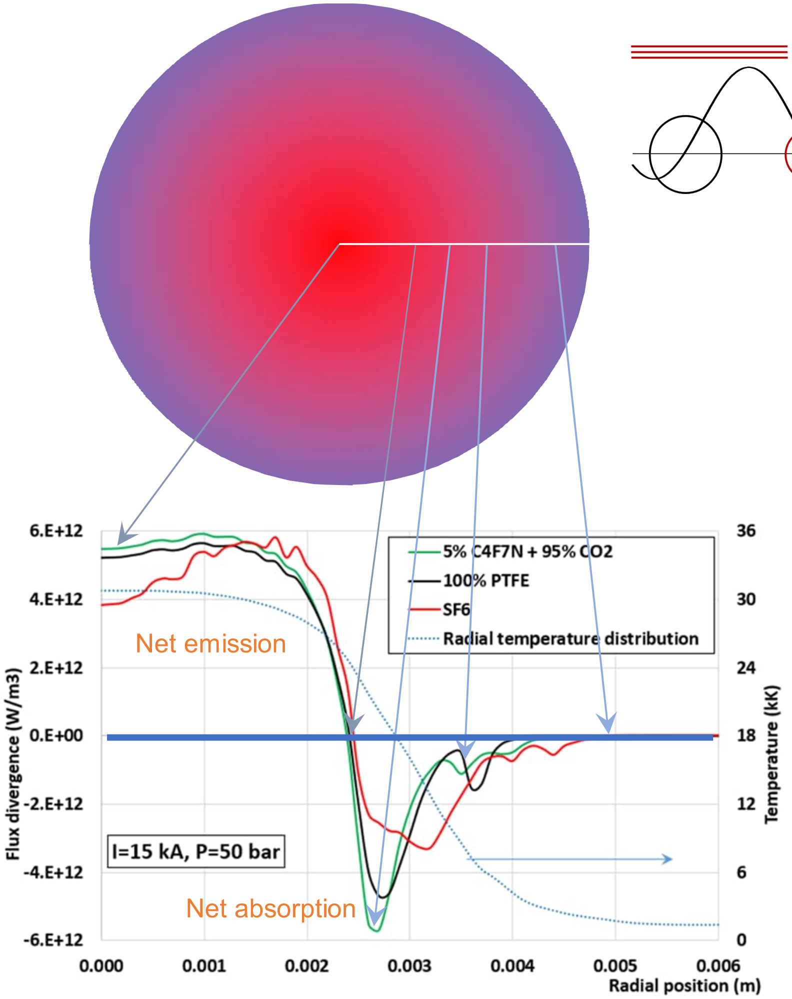
PART II: Radiation

Radiative energy transfer

- Radiative energy flux due to travelling of photons
- Flux varies in space because of emission and absorption of photons;
- Net effect changes significantly across the arc column

- Radiation transfer in $C_4F_7N+CO_2$ mixture) is slightly different from that in SF_6 for given temperature profile and pressure
- The temperature range of absorption leads to a characteristic temperature profile of the arc
- Larger absorption in the outer region leads to a thicker arc
- Differences between gases for the high current arc are not very pronounced

Gas Medium	Net emission from arc core (W/m)	Net absorption at arc edge (W/m) and % of net emission from arc core	Net radiative power leaving arcing gas (W/m) and % of net emission from arc core
SF_6	8.35E+07	6.88E+07 (82%)	1.47E+07 (18%)
5% C_4F_7N+95% CO_2	7.80E+07	5.99E+07 (77%)	1.82E+07 (23%)
PTFE (C_2F_4)	7.60E+07	5.63E+07 (74%)	1.97E+07 (26%)

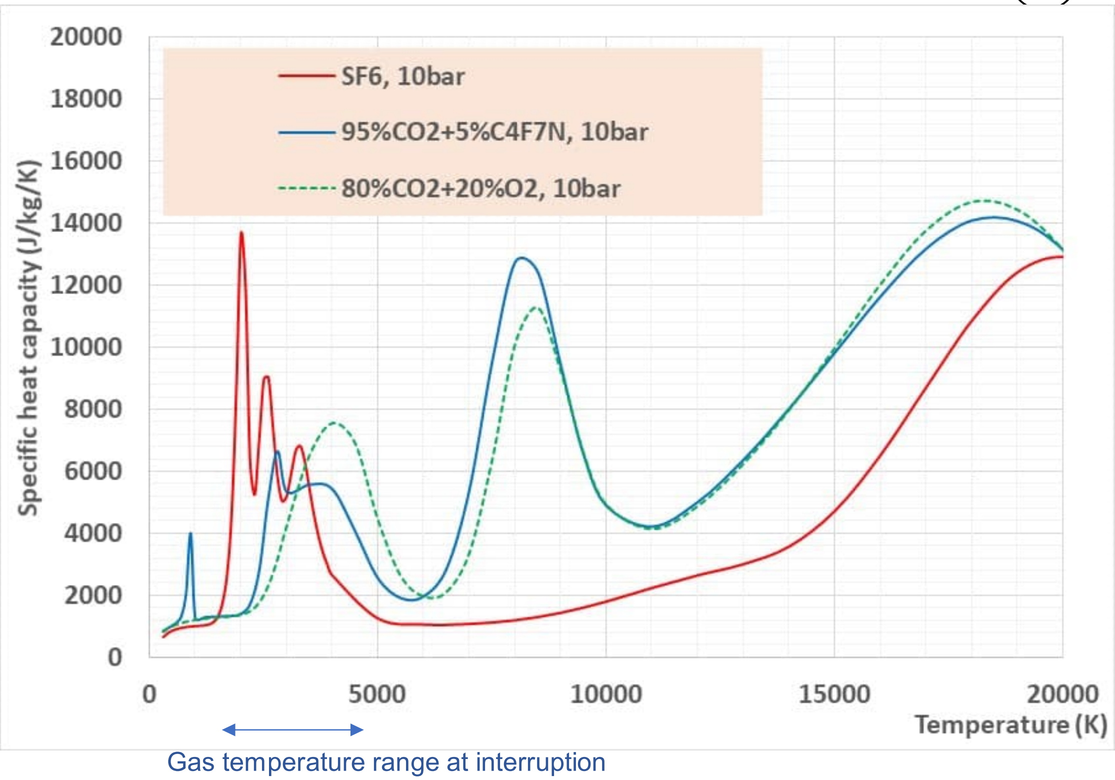


There is net emission of radiation from the arc centre, but a considerable fraction is re-absorbed at the arc edge

PART II: Material properties relevant for current interruption

Specific heat capacity at constant pressure

- Reflects the ability of a unit mass of a gas to store energy when temperature changes
- Nonlinear function of temperature
- Peaks result from chemical reactions and ionisation
- SF_6 is able to store more energy in its non-conducting temperature range below 4000K. This helps absorbing the thermal energy during the arc cooling process
- CO_2 based gas mixtures are considerably different from SF_6

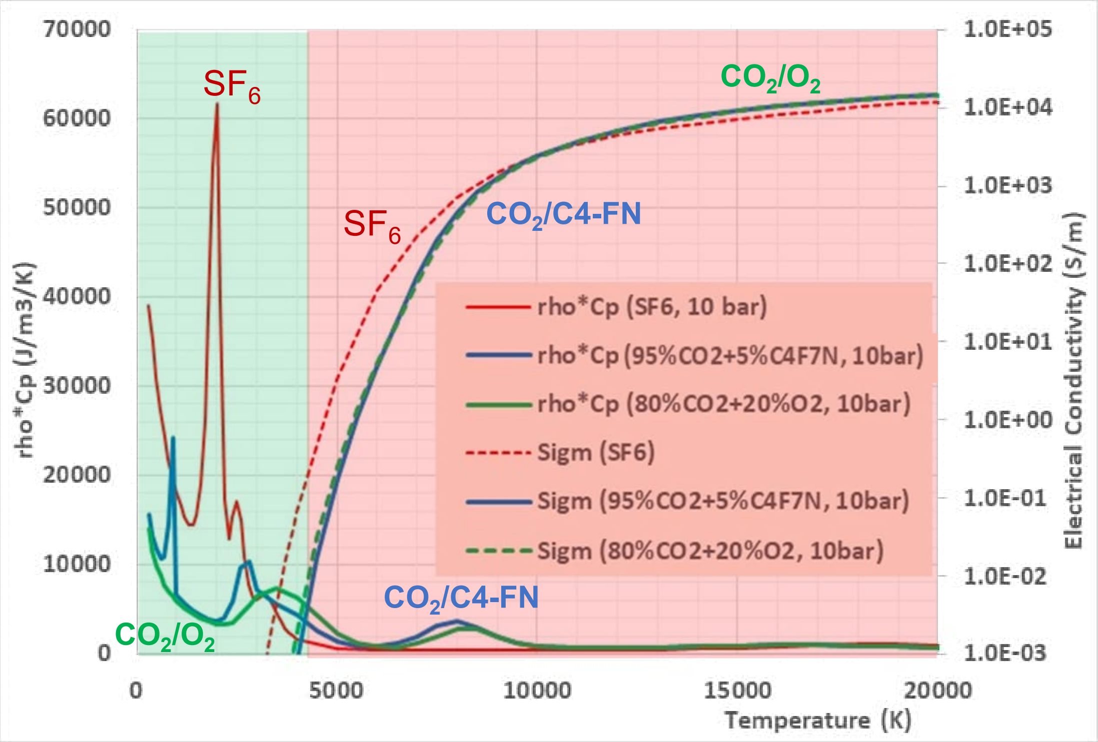


At interruption temperature, CO_2 based gases can store less energy than SF_6

PART II: Material Properties relevant for current interruption

Energy density in gas

- The occurrence of ρ·Cp peaks with CO_2 based gas mixtures above the conducting temperature increases the energy content in the arc column
- More cooling power will be needed to reduce the arc temperature in these gases
- The electrical conductivity of CO_2/O_2 mixtures are much lower than SF_6 below 5000 K
- C4-FN mixture similar to CO_2/O_2
- From this it can be expected that C4-FN/CO_2 mixtures might be only slightly better in thermal interruption performance than CO_2/O_2 mixtures

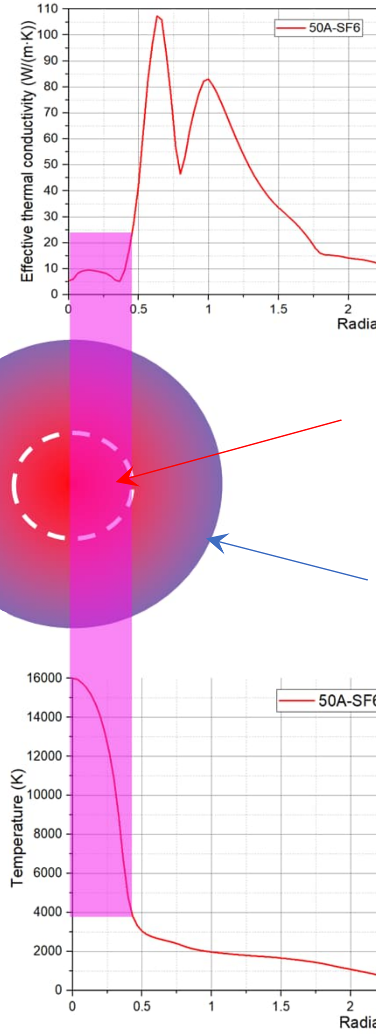


Compared with SF_6, CO_2 based gas mixtures require more heat to be removed from the conducting column

PART II: Arc radius

Turbulence effect

- Turbulence enhances heat transfer where temperature gradient exists
- Turbulent cooling effect can be quantified by an effective thermal conductivity K_t, which is related to $\rho \cdot C_p$
- At low current, arcs in turbulent flow have very different temperature profiles in different gases.
- Large arc radius means turbulent cooling at the surface is less effective to cool the more distant hot core
- A thin arc is easier to cool



In SF_6 arcs, turbulence enhanced energy transfer is strongest in the region immediately surrounding the conducting column

Hot core

Conducting boundary of arc column

In SF_6, arc column is thin and temperature gradient inside the conducting column is steep

Temperature profile and arc radius are important for arc cooling

SF_6

Conducting core

(1) Low ρC_p

(2) Low K_t

(3) Steep temp. gradient

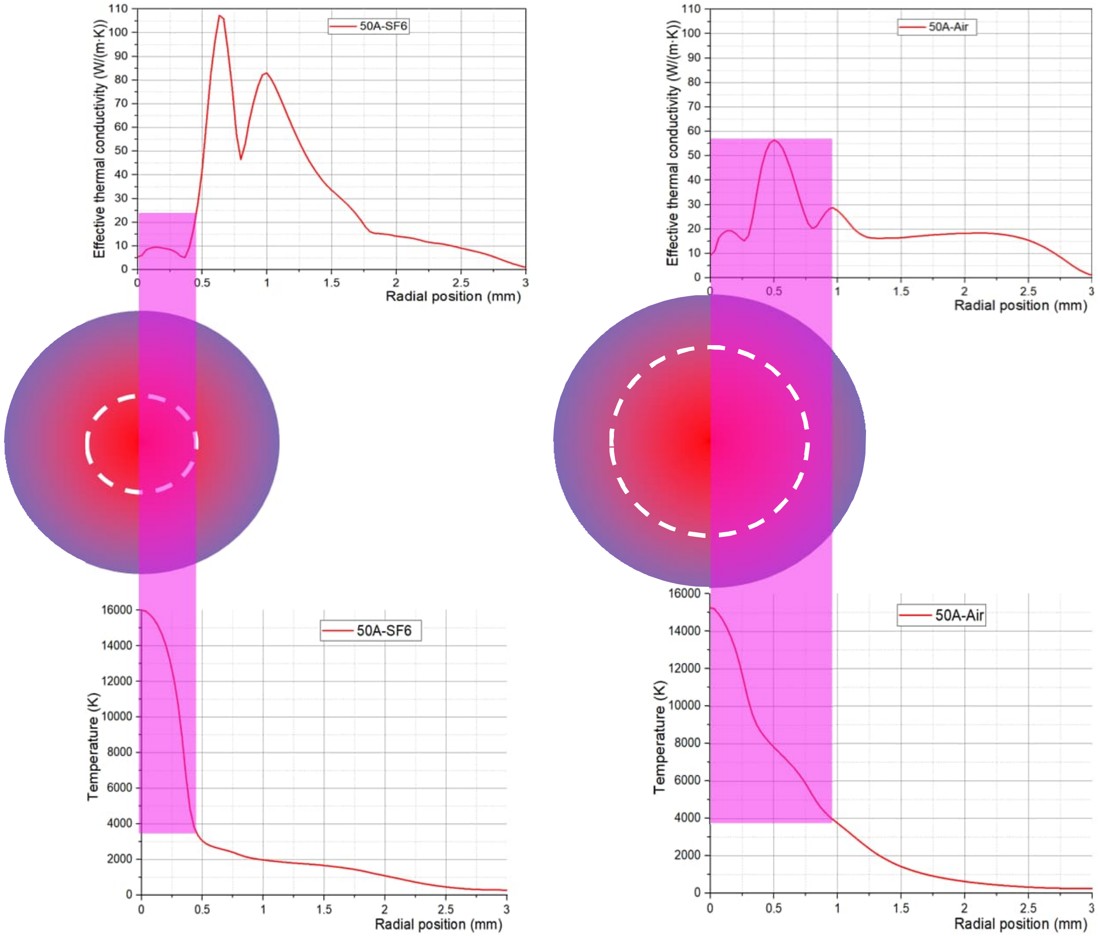
(4) Thin core column

At boundary of conducting core

(1) Fast increasing K_t spreads heat

(2) High ρC_p absorbs more energy

(3) Transition to low temp. gradient



Air

Conducting core

(1) Peaks of ρC_p

(2) Peaks of K_t

(3) Reduced temp. gradient

(4) Core broadened

At boundary of conducting core

1) Moderate K_t

(2) Moderate ρC_p

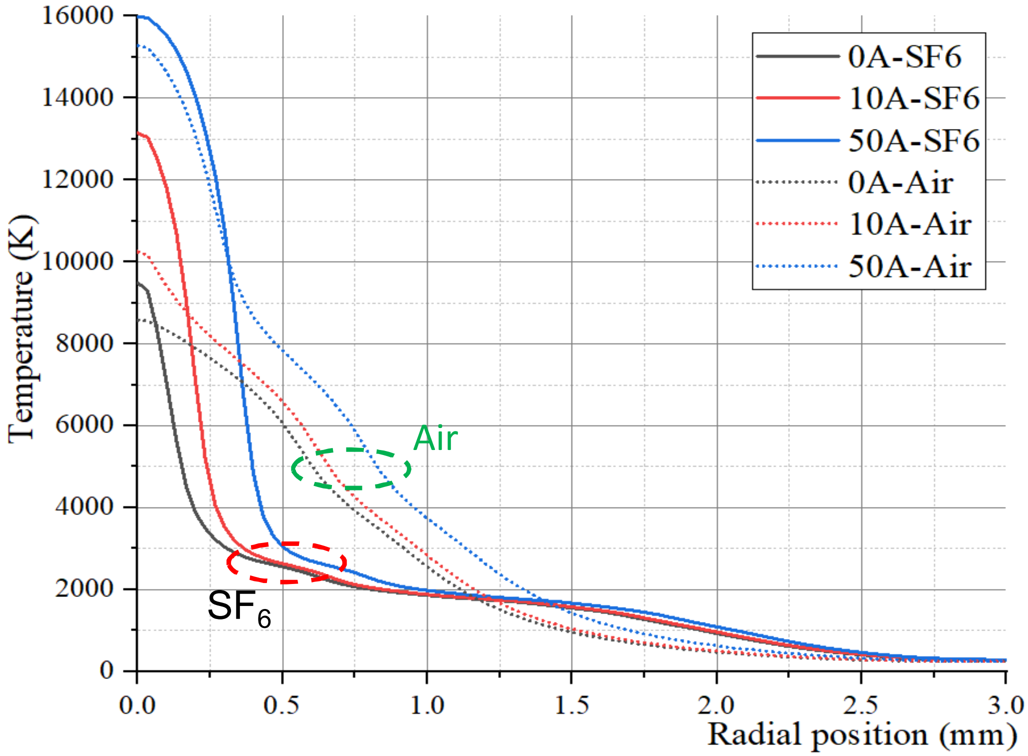
(3) Temperature gradient not significantly reduced

Temperature profile in air much larger than in SF_6. CO_2 based mixtures are in between these extremes

PART II: Arc Temperature Profile

Radial temperature profile towards CZ

- Approaching current zero the SF_6 arc reduces its radius more rapidly than the non- SF_6 arc
- The energy stored in the SF_6 arc is much lower than that in non- SF_6 arcs owing to its thin arc column and low $\rho \cdot C_p$
- Among radiation, convection, conduction and turbulent cooling, turbulence is the dominant energy removal mechanism approaching current zero
- Arc profile is an indicator for interruption, direct interruption performance still not sufficiently precise to predict



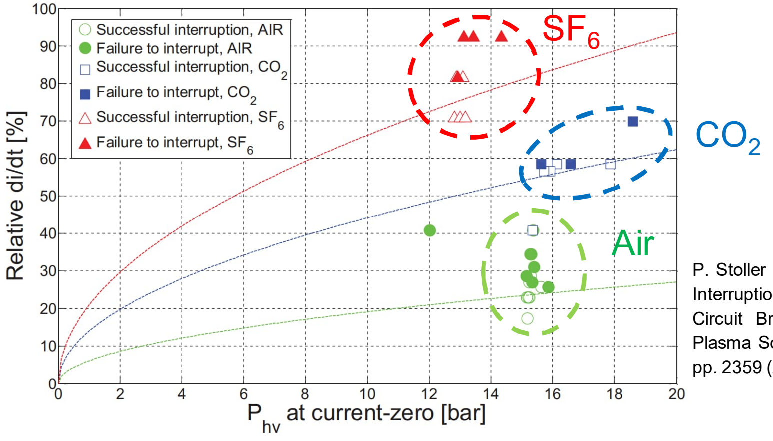
Under identical discharge conditions in a nozzle, non- SF_6 arcs have larger diameters than SF_6 arcs.

PART II: Arc Temperature Profile

Arc temperature profile and thermal interruption

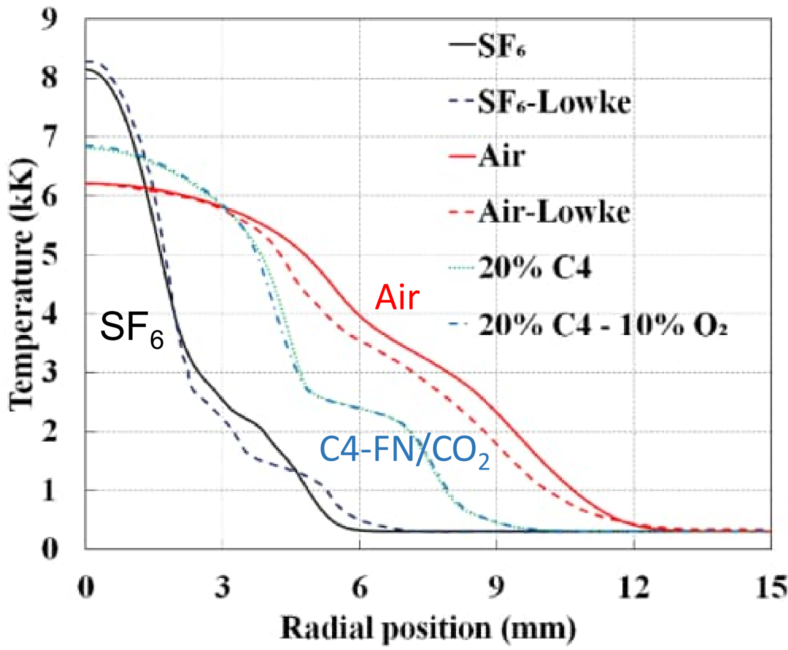
- Calculations show that temperature profile in CO_2 based mixtures is in between SF_6 and air
- Roughly this might explain qualitatively why CO_2 in experiments has higher thermal interruption capability than air but lower than SF_6

Experiment



P. Stoller et al., "CO_2 as an Arc Interruption Medium in Gas Circuit Breakers", IEEE Trans Plasma Science, Vol. 41, No. 8, pp. 2359 (2013)

Simulation



Narayanan V R T, Gnybida M and Rümpler C, "Transport and radiation properties of C_4F_7N-CO_2 gas mixtures with added oxygen", J. Phys. D: Appl. Phys. 55 (2022)

Temperature profile in CO_2 based mixtures is in between SF_6 and air, this correlates with interruption performance

PART II: Thermal interruption comparison

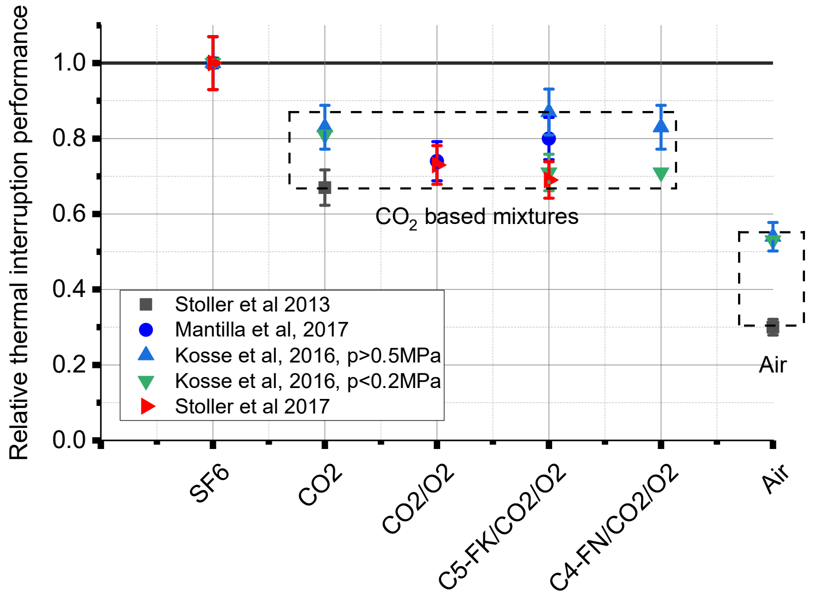
Comparison of material properties and

calculations of arc temperature profile indicate ranking:

Air < $CO_2 \leq CO_2$/C4-FN < SF_6

Experimental evidence (SF_6 = 1)

- CO_2 and CO_2/O_2 is in the range: 67-83% of SF_6
- CO_2 based mixtures with C4-FN and C5-FK are in the range 67-87% of SF_6
- Adding C4-FN or C5-FK does not seem to significantly change performance, i.e. within uncertainties
- In agreement with expectations based on material parameters



Stoller 2013: P. Stoller et al., “CO_2 as an Arc Interruption Medium in Gas Circuit Breakers”, IEEE Trans Plasma Science, Vol. 41, No. 8, pp. 2359, 2013

Mantilla 2017: J. D. Mantilla, Kriegel, and Panousis, ‘Switching Interruption Performance Comparison between SF_6, CO_2 and Fluoroketones-based mixtures in HVCB’, CIGRÉ Winnipeg 2017 Colloquium Study Committees A3, B4 & D1, September 30 – October 6, 2017

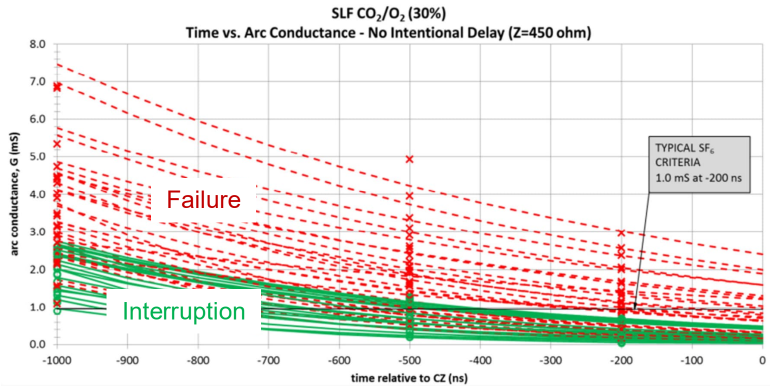
Kosse 2016: S. Kosse, P.G. Nikolic and G. Kachelriess, “HOLISTIC EVALUATION OF THE PERFORMANCE OF TODAY’S SF_6 ALTERNATIVES PROPOSALS”, CIRED 24th International Conference on Electricity Distribution Glasgow, 12-15 June 2017, paper 0819

Stoller 2017: P.C. Stoller, C.B. Doiron, D. Tehlar, P. Simka and N. Ranjan, “Mixtures of CO_2 and $C_5F_{10}O$ Perfluoroketone for High Voltage Applications”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 24, No. 5; October 2017, pp 2712-2721

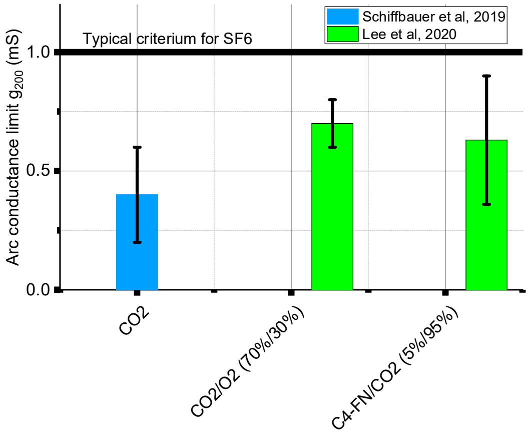
Under same conditions CO_2 based mixtures have about 20-30% lower thermal interruption performance than SF_6

PART II: Arc conductance decay

- Due to the reduced cooling and thicker arc column: Conductance decay slower than SF_6
- Close to CZ (200 ns before) the arc conductance g_{200} relates to the interruption performance, i.e. is an indicator of performance
- Critical g_{200} value about a factor of two lower than in SF_6



D. Schiffbauer et al., ‘High Voltage F-gas Free Switchgear applying CO_2/O_2 Sequestration with a Variable Pressure Scheme’, CIGRE-IEC 2019 Conference on EHV and UHV (AC & DC) ,April 23-26, 2019



Lee W Y et al, “Comparison of the Interrupting Capability of Gas Circuit Breaker According to SF_6, g^3 and CO_2/O_2 Mixture”, Energies 2020, 13, 6388; doi:10.3390/en1

D. Schiffbauer et al., ‘High Voltage F-gas Free Switchgear applying CO_2/O_2 Sequestration with a Variable Pressure Scheme’, CIGRE-IEC 2019 Conference on EHV and UHV (AC & DC) ,April 23-26, 2019

Under same conditions CO_2 based mixtures show a slower conductance decay around CZ

PART II: Post arc current

- Post arc current (PAC) duration with CO_2 based mixtures is longer compared to SF_6
- Typical duration from L90 and L75 tests is in the range of 2-6 us
- Measured PAC peaks are typically in the range of 0.5-10 A. The reason for the large difference in measurements is still not clarified
- Large variation of PAC peak and duration possibly due to blow conditions, arc zone design, gas and on circuit parameters
- Different from SF_6 with PAC peaks well below 0.5 A and duration of less than 1 us. Since difficult to measure variations possibly less visible in SF_6

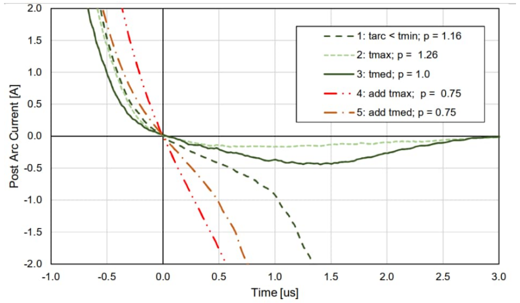
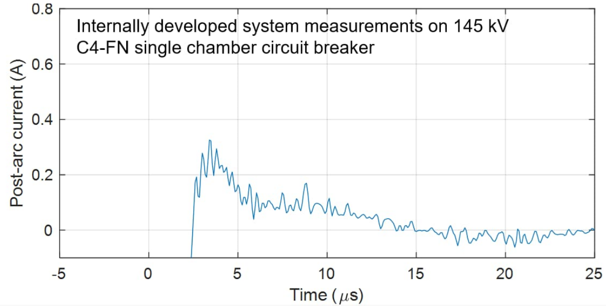
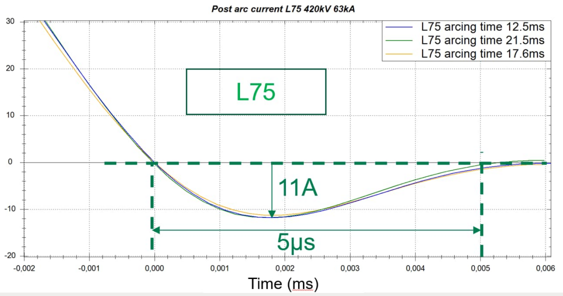


Figure 2.8 - Measurements of PAC in a C5-FK / O_2 / CO_2 gas mixture [91]

J. D. Mantilla, Claessens, and Kriegel, 'Environmentally friendly perfluoroketones-based mixture as switching medium in high voltage circuit breakers', e-cigré, Aug. 26, 2016.



CIGRE Paris Session 2022



CIGRE Paris Session 2022

Significant differences in PAC between SF_6 and CO_2 based mixtures but also between different measurements

PART II: Design related properties

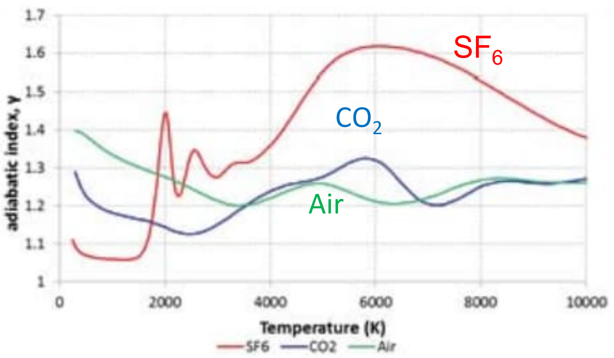
- So far intrinsic material properties were compared
- By design the conditions at CZ can be adapted:
    - Blow pressure
    - Axial pressure profile
    - Blow gas temperature
- Important material parameters for this are:
    - Adiabatic index ($\gamma=c_p/c_v$)
    - Velocity of sound
- Together with details of the arc zone (flow cross sections etc) they determine the pressure and temperature of the blow gas at CZ
- The ablation of PTFE nozzles will affect the composition of blow gas

Higher adiabatic index leads to higher pressure build up, higher sound velocity leads to faster changes in pressure

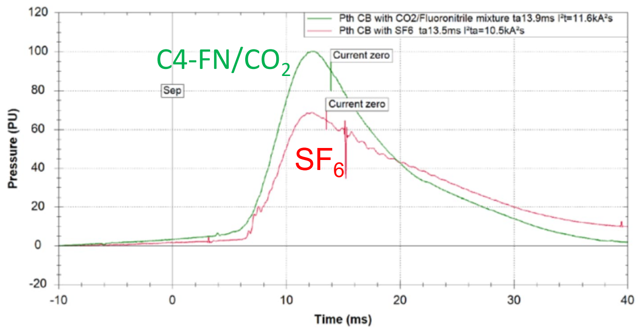
PART II: Design related properties

Adiabatic index (γ)

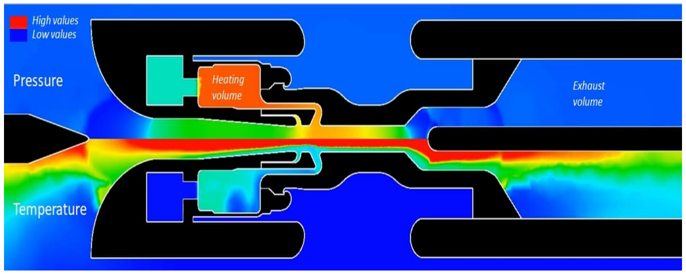
- Lower for SF_6 below 1900 K, which is the typical range for HV CB heating chamber and blow gas
- Pressure in a volume scales with energy input and (γ-1)
- Heating volume pressure and exhaust pressure are affected.
- The heating volume pressure is, therefore, higher in CO_2 based mixtures compared to SF_6



P. C. Stoller, M. Seeger, A. A. Iordanidis, and G. V. Naidis, 'CO_2 as an Arc Interruption Medium in Gas Circuit Breakers', IEEE Trans. Plasma Sci., vol. 41, no. 8, pp. 2359–2369, Aug. 2013



Bousoltane, Vigoroux, Y. Kieffel, Zhou, and P. Robin-Jouan, 'Performance evaluation of CO_2 and fluoronitrile mixture in comparison with SF_6', Cigre Sess. 47, 2018.

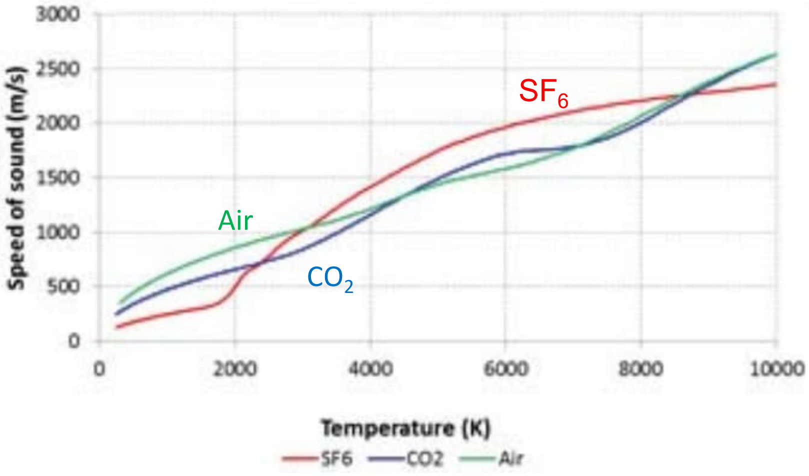


Higher adiabatic index leads to higher pressure build up

PART II: Design related material properties

Speed of sound

- Lower for SF_6 below 2000K
- This affects outflow from heating volume, i.e. in CO_2 based mixtures pressure drop is faster
- This might be considered in the design, e.g. by adaption of flow cross sections
- Faster removal of hot gas from the arc zone with CO_2 based mixtures due to higher velocity

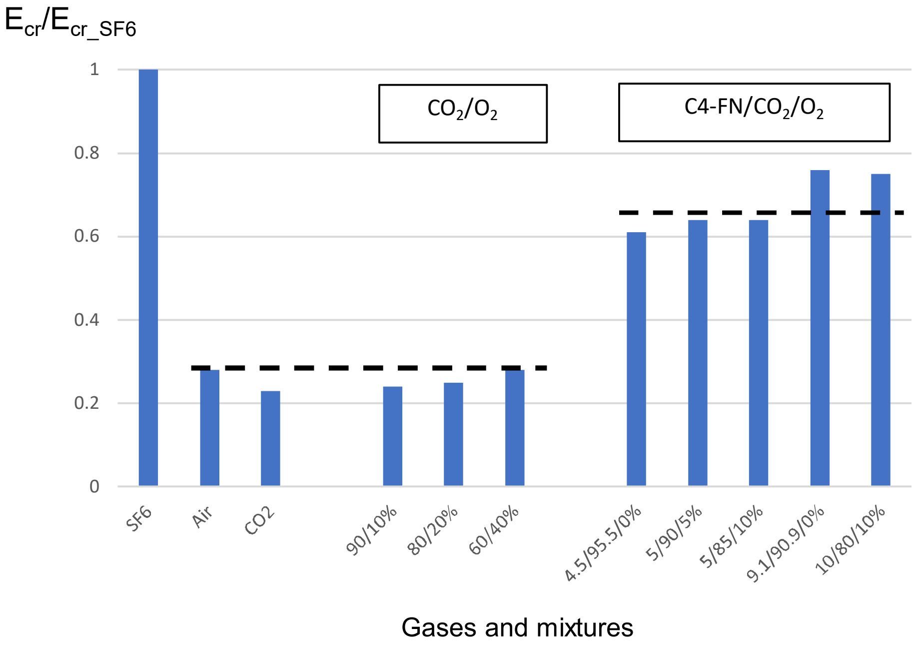


P. C. Stoller, M. Seeger, A. A. Iordanidis, and G. V. Naidis, 'CO_2 as an Arc Interruption Medium in Gas Circuit Breakers', IEEE Trans. Plasma Sci., vol. 41, no. 8, pp. 2359–2369, Aug. 2013

Speed of sound is higher in CO_2 based mixtures compared to SF_6

PART II: Critical Field

- Critical field (at same pressure) in CO_2 much lower than in SF_6
- Fluorinated additives to CO_2 can increase significantly the critical field due to positive synergy
- CO_2/O_2 mixtures are in the range of 25% of SF_6
- C4-FN/CO_2/O_2 mixtures with 5% admixtures are in the range of 60 % of SF_6
- Lower critical field can be, as for insulation, compensated by pressure increase



CO_2 mixtures with C_4F_7N show synergy, a small amount increases significantly the critical field

PART II: Dielectric recovery

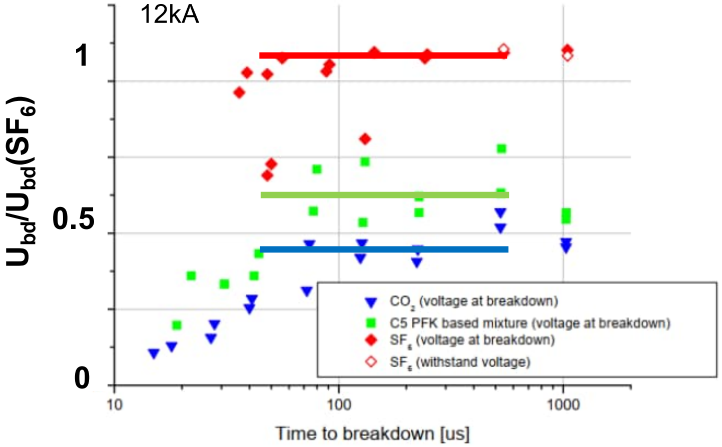
- Rate of rise of recovery is known to scale with pressure, temperature and critical field

  $du/dt \sim E_{cr}(p,T)$

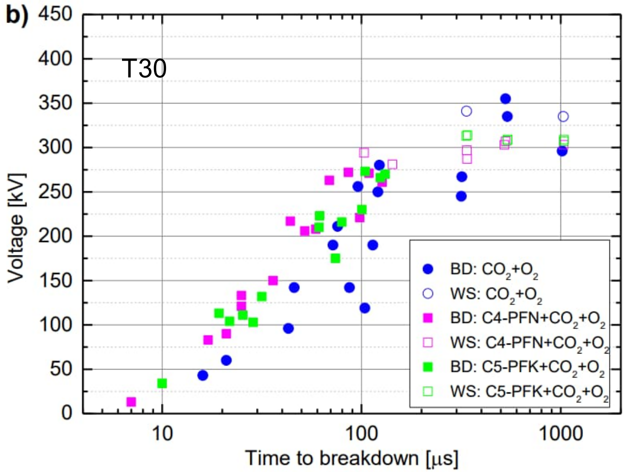
- For similar temperature decay and pressure, it is expected (see previous slide) that the recovery scales as

  CO_2 (25%)< CO_2/C4-FN or CO_2/C5-FK (60%) < SF_6 100%)

- Details depend % of admixture, design, blow conditions, short circuit current, non-equilibrium effects
- SF_6 recovers faster than CO_2 based gases
- CO_2 based gases with additives recover faster than CO_2/O_2



P.C. Stoller, C.B. Doiron, D. Tehlar, P. Simka and N. Ranjan, "Mixtures of CO_2 and $C_5F_{10}O$ Perfluoroketone for High Voltage Applications", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 24, No. 5; October 2017, pp 2712-2721



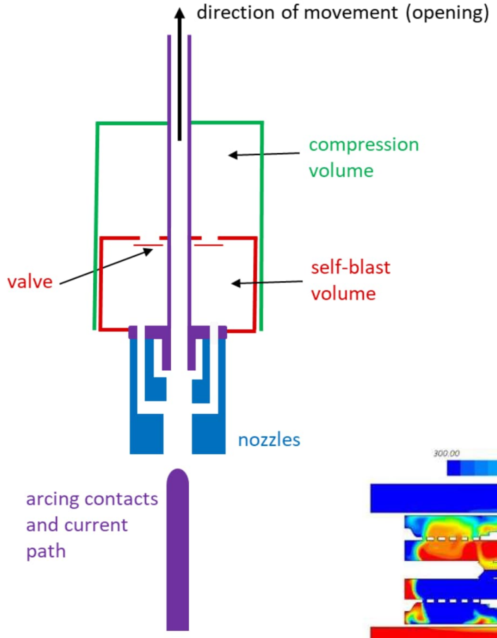
Radisavljevic B et al, "SWITCHING PERFORMANCE OF ALTERNATIVE GASEOUS MIXTURES IN HIGH-VOLTAGE CIRCUIT BREAKERS", Proc. 20th International Symposium on High Voltage Engineering, Buenos Aires, Argentina, August 27 – September 01, 2017

Dielectric recovery ranking based on critical field confirmed by experiments

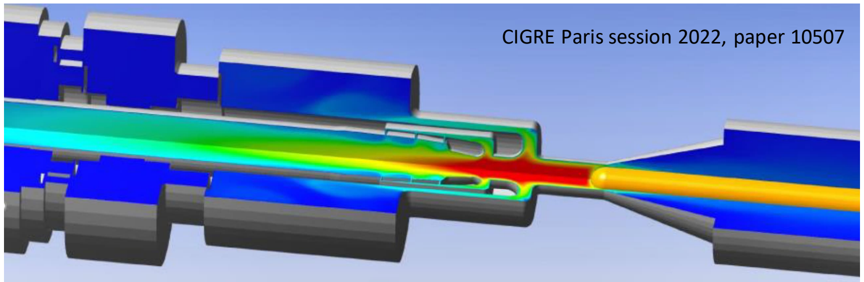
Part II Design modifications to adapt to the new media

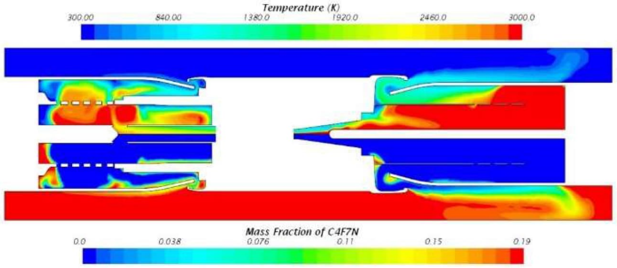
Certain modifications are necessary to adapt to the “less favorable” parameters of the new media

- Higher filling pressure
- Higher contact separation speed may be required
- Larger compression volume
- Re-design of nozzle and arcing volume e.g. increase nozzle length and reduce its diameter
- Adjustment of electrical field control near contacts



CIGRE Paris session 2022, paper 10507


CIGRE Paris session 2022, paper 10507



CIGRE Paris session 2022, paper 10966

Design modifications are essential to accommodate the “new gases”

PART II: Summary and outlook

Thermal interruption and early dielectric recovery

- Strongly coupled processes, many parameters involved
- Difficult to simulate
- Simple predictions based on material properties remain qualitative
- For thermal interrupting in CO_2/O_2 mixtures, CO_2 is a good performer
- For dielectric recovery, addition of low percentage (≈ 5%) C4-FN is of importance. With pressure increase a performance close to SF_6 can be reached, as for the insulation

Outlook

- Experimental benchmarks needed
- Non-equilibrium material properties are needed
- Simulations of the coupled process are needed including radiation, turbulence, validated turbulence models etc
- Effect of electron attachment on thermal interruption needs further clarification
- 3D arc instabilities can lead to fluctuation in interruption performance and need further investigations

Current Zero Club