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Pro-Science

Combustion experiments with homogeneous and gradient H_2-CO-air mixtures in semi-confined geometries

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Supported by:
(Support code: 1501545B)

Federal Ministry
for Economic Affairs
and Energy

Outline

- Project 1501545
- Test Facility
- Experiments with homogeneous H_2-CO-air mixtures
- Generation of H_2-CO-air gradient-mixtures
- Experiments with H_2-CO-air gradient-mixtures
- Summary

Introduction

- In many severe accident scenarios, as e.g. a nuclear reactor accident or an accident of a H_2-powered vehicle in a tunnel the formation of large quantities of H_2 and CO is conceivable.
- In these scenarios H_2-CO-air mixtures are formed that might accumulate below ceilings or in other semi-confined geometries,
- Since CO is flammable, H_2-CO-air mixtures, same as H_2-air mixtures, can cause high pressure loads during a combustion and might cause strong structural damage to a facility.
- For the evaluation of the damage potential associated with H_2-CO-air layers and as a basis for the development of mitigation measures the combustion behavior of such mixtures in semi-confined geometries has to be investigated.

Introduction

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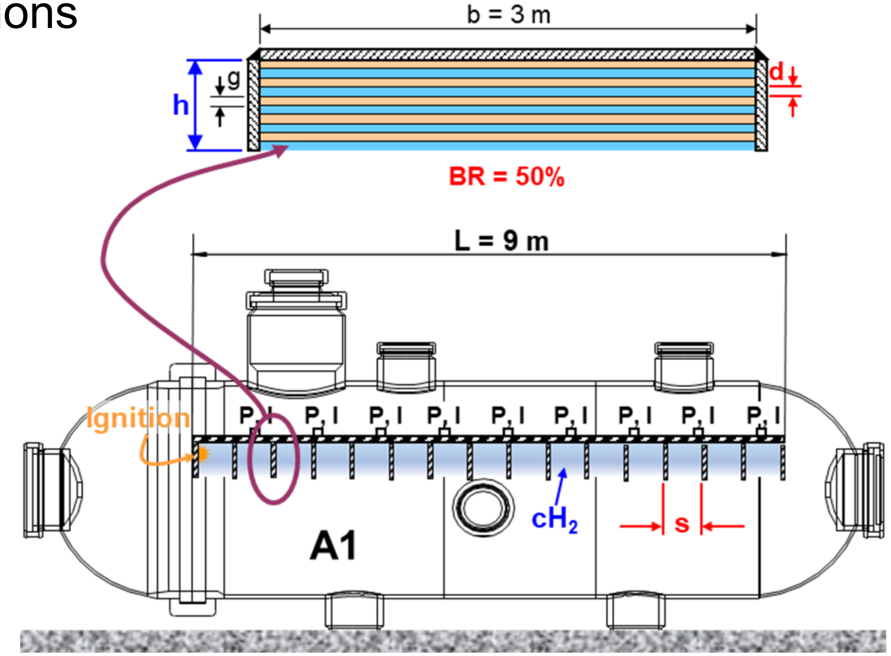
- The burning behavior of **H_2-air mixtures** in semi-confined geometries was investigated by PS/KIT and TUM (Chair of Thermodynamics at Technical University Munich) in 2 previous research projects.
- Main outcome of the large-scale experiments with **homogeneous H_2-air mixtures** in semi-confined geometries with different
  - H_2-concentrations (cH_2),
  - layer heights (h),
  - obstacle blockage ratios (BR), spacings (s) and orientations

  at PS/KIT are criteria for the
  - onset of Flame Acceleration (FA)

    $\sigma^* = \sigma^*_0 (1 + K \cdot s/h)$ with $K = 0.175$
  - Deflagration-to-Detonation Transition (DDT) $h/\lambda = 13.5$
  - and the detonation propagation $d/\lambda = 3$
- For **H_2-air gradient-mixtures** in same geometry: burning behavior is governed by maximum concentration in gradient ➔ **Concept of Maximum Concentration**
- In the current project these results shall be extended/ transferred to **H_2-CO-air mixtures**.



Test Facility

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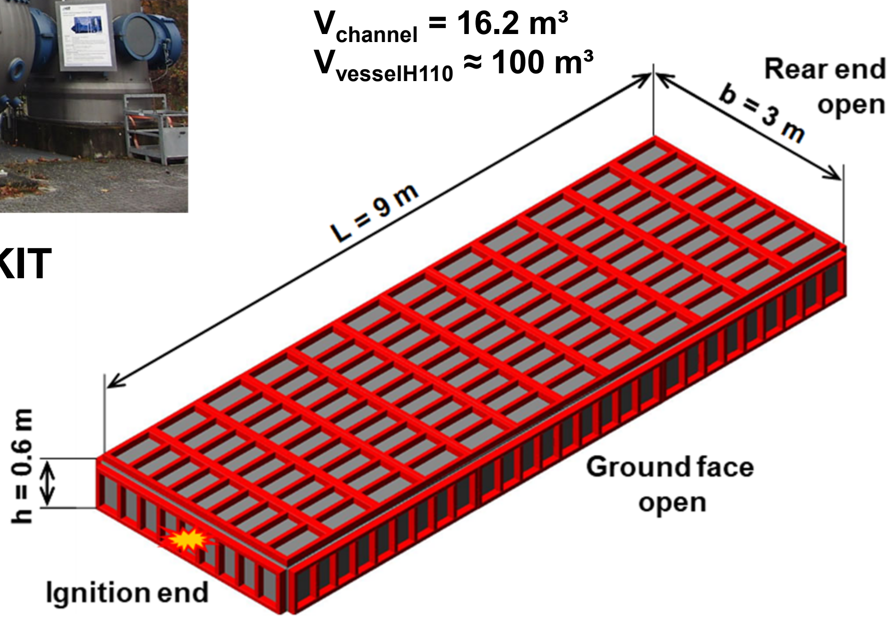
Test-channel in safety-vessel H110

Safety-Vessel H110 at KIT
- Length: approx. 12 m
- Diameter: approx. 3.3 m
- Volume: approx. 98 m^3
- max. Pressure (static): 100 bar



Test Channel
- Inner Dimensions: 9 x 3 x 0.6 m,
- Ground face and rear end open,
- Ignition at closed front end.

Test Facility

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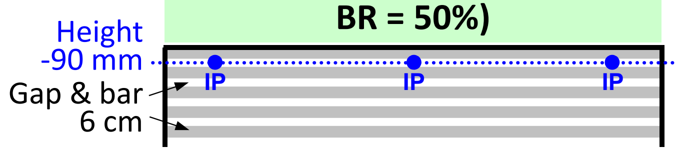
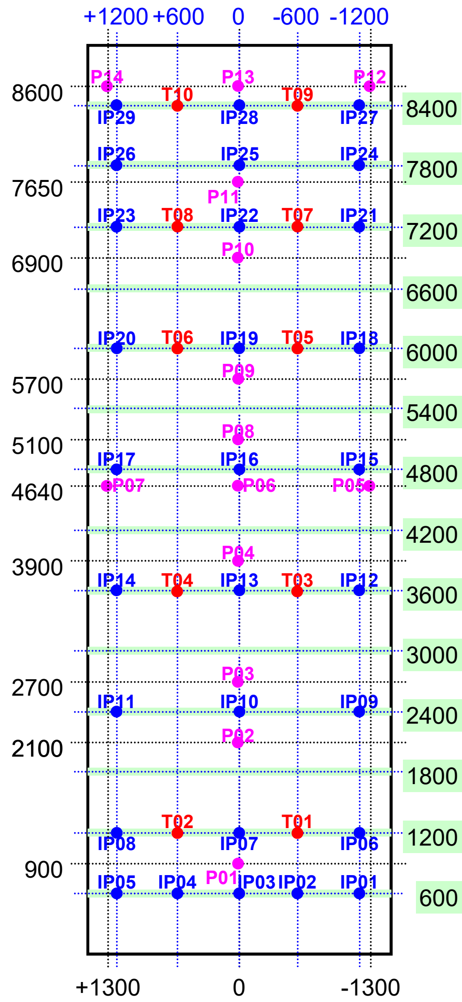
Test channel instrumentation

- Obstacle configuration similar to “standard-configuration” of first project (➔ many experiments for comparison)

Horizontal Obstacles
(6 wooden bars 300 x 6 x 4 cm, BR = 50%)



- Sensors:
  - 29 ionization probes (in uppermost bar of obstacle),
  - 10 modified thermocouples (flame detection),
  - 14 fast pressure sensors in adapters in channel ceiling,
- All signals are recorded simultaneously with a TransCom-RackX Transient Recording System (MF Instruments), Frequency: usually 100 kHz (10 µs)
- Instrumentation similar to earlier configurations (➔ good comparability of measurements).



Experiments with homogeneous H_2-CO-air mixtures

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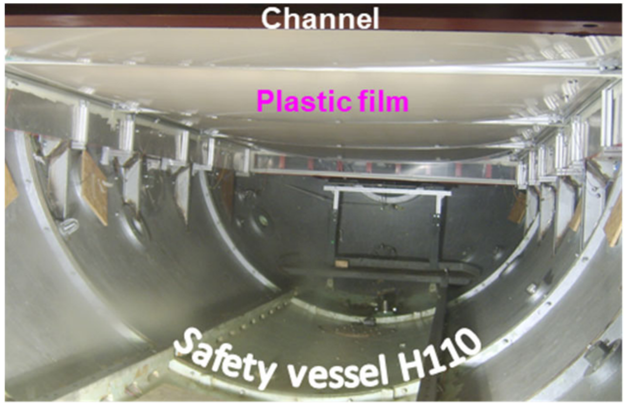
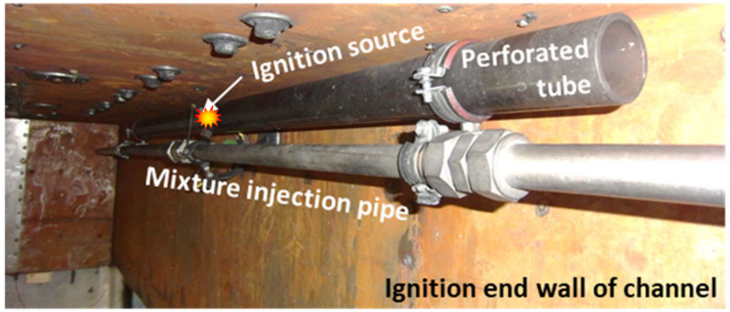
Test procedure for homogeneous H_2-CO-air mixtures

- For filling the open ground face is sealed with a thin plastic film.



- "Purging" of channel with test-mixture until $cMix_{out}$ = $cMix_{in}$,



- Very slow filling procedure:
  concentration approaches targeted value asymptotically.
- After end of filling procedure film is cut by heating wires,
- Immediately after the cut (film is still floating) mixture is ignited in a perforated tube.

Test Matrix for experiments with homogeneous H_2-CO-air mixtures

Experi-ment	Fuel {Vol%]	cH_2 [Vol%]	cCO [Vol%]	Ratio cH_2 / cCO
300	**14** (13.60)	**14** (13.60)	**0** (0)	100 / 0
301	**14** (13.88)	**10.5** (10.46)	**3.5** (3.42)	75 / 25
302	**16** (15.86)	**8** (8.04)	**8** (7.83)	50 / 50
303	**16** (15.81)	**12** (11.92)	**4** (3.89)	75 / 25
304	**18** (18.02)	**9** (9.01)	**9** (9.01)	50 / 50
305	**15** (14.89)	**11.25** (11.24)	**3.75** (3.66)	75 / 25
306	**17** (16.99)	**8.5** (8.48)	**8.5** (8.51)	50 / 50
307	**16** [16.02)	**4** (4.08)	**12** (11.94)	25 / 75
308	**20** (19.83)	**5** (5.02)	**15** (14.81)	25 / 75
309	**18** (18.13)	**4.5** (4.56)	**13.5** (13.57)	25 / 75
310	**20** (20.08)	**10** (10.05)	**10** (10.03)	50 / 50
311	**19** (19.17)	**4.75** (4.72)	**14.25** (14.49)	25 / 75
312	**20** (20.04)	**15** (14.96)	**5** (5.08)	75 / 25
313	**19** (18.85)	**14.25** (14.2)	**4.75** (4.64)	75 / 25
314	**21** (21.03)	**10.5** (10.52)	**10,5** (10.51)	*50 / 50*
315	**22** (22.12)	**5.5** (5.52)	**16.5** (16.59)	25 / 75

Bold: planned concentration (in brackets): measured concentration

- In total
  - 1 reference test with H_2-air mixture and
  - 15 experiments with H_2-CO-air mixtures planned,
- initially only 2 ratios H_2/CO (75/25 and 50/50),
- later H_2/CO-ratio (25/75) was added.

Experiments with homogeneous H_2-CO-air mixtures

Test Matrix for experiments with homogeneous H_2-CO-air mixtures

Ratio cH_2 / cCO	Experi-ment	Fuel {Vol%]	cH_2 [Vol%]	cCO [Vol%]	$V_{avg(End)}$ [m/s]	$P_{avg(End)}$ [bar]	σ [-]	λ [mm]
100 / 0	300	**14** (13.60)	**14** (13.60)	**0** (0)	201	1.66	4.420	530.5
75 / 25	301	**14** (13.88)	**10.5** (10.46)	**3.5** (3.42)	123	0.81	4.614	440.0
	305	**15** (14.89)	**11.25** (11.24)	**3.75** (3.66)	276	3.41	4.836	285.6
	303	**16** (15.81)	**12** (11.92)	**4** (3.89)	**474**	**4.49**	**5.033**	**195.3**
	313	**19** (18.85)	**14.25** (14.2)	**4.75** (4.64)	**664**	**5.50**	**5.653**	**55.47**
	312	**20** (20.04)	**15** (14.96)	**5** (5.08)	**1233**	**10.7**	**5.888**	**3.596**
50 / 50	302	**16** (15.86)	**8** (8.04)	**8** (7.83)	106	0.69	5.140	158.3
	306	**17** (16.99)	**8.5** (8.48)	**8.5** (8.51)	325	2.14	5.380	97.37
	304	**18** (18.02)	**9** (9.01)	**9** (9.01)	**424**	**3.76**	**5.592**	**63.93**
	310	**20** (20.08)	**10** (10.05)	**10** (10.03)	**624**	**6.08**	**5.996**	**33.44**
	314	**21** (21.03)	**10.5** (10.52)	**10.5** (10.51)	**1162**	**16.0**	**6.166**	**25.66**
25 / 75	307	**16** [16.02)	**4** (4.08)	**12** (11.94)	19	0.60	5.269	151.1
	309	**18** (18.13)	**4.5** (4.56)	**13.5** (13.57)	102	1.25	5.711	68.20
	311	**19** (19.17)	**4.75** (4.72)	**14.25** (14.49)	174	1.18	5.927	49.73
	308	**20** (19.83)	**5** (5.02)	**15** (14.81)	**418**	**2.85**	**6.044**	**41.80**
	315	**22** (22.12)	**5.5** (5.52)	**16.5** (16.59)	**724**	**4.05**	**6.437**	**26.56**

Black: Slow (subsonic) combustion (M < 1) Blue: Fast (sonic) combustion (M > 1) Red: Quasi-detonation (v_{av} ~ (0.6-0.85)·D_{CJ}, M >> 1)

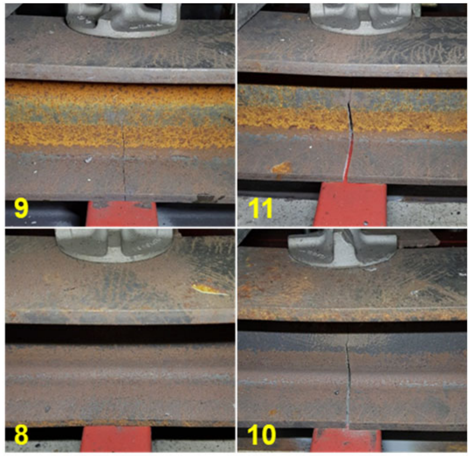
- Transitions from slow to fast deflagration determined.
- Transition to detonation determined for (75/25) and (50/50).
- Detonation limit for (25/75) approached but not crossed due to lack of time and strong loads to the facility.

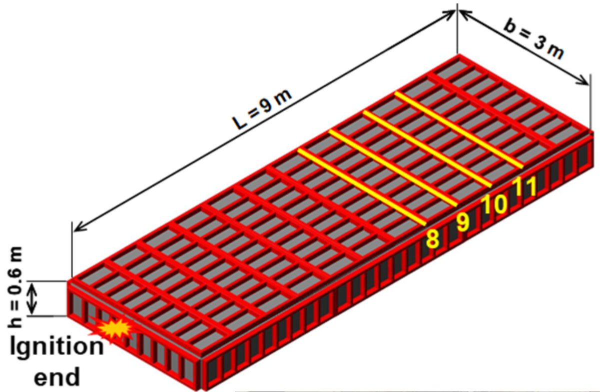
Experiments with homogeneous H_2-CO-air mixtures

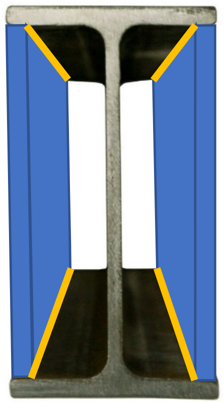
Damages to the facility due to strong combustion loads

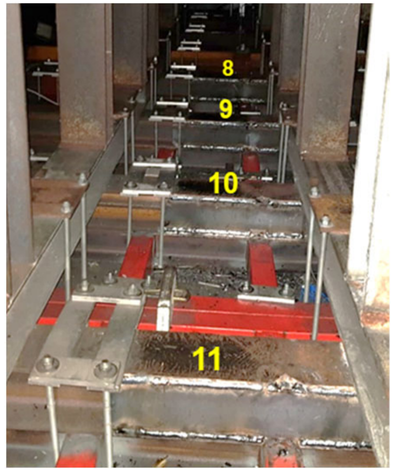
- During experiments beam obstacles are usually stripped from channel ceiling or, in case of fast flames, destroyed.
- But after several experiments with fast flames cracks were detected in beams reinforcing the channel ceiling.
- Replacement of beams not possible within project time frame, so cracks repaired by welding metal sheets into open sides of beams.
- Repaired beam sections withstood loads, but further cracks at other beams and positions detected after every following test with fast flames, resulting in

Strong time delay!





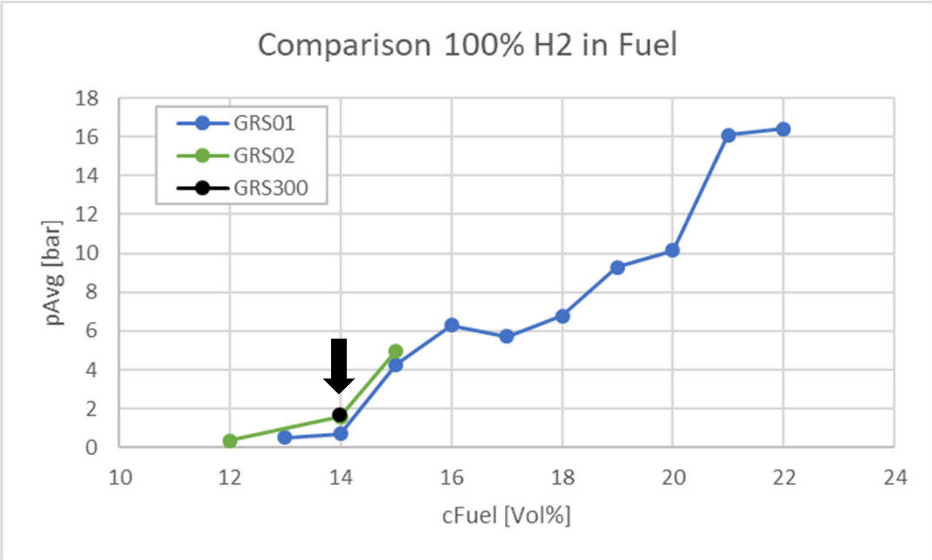


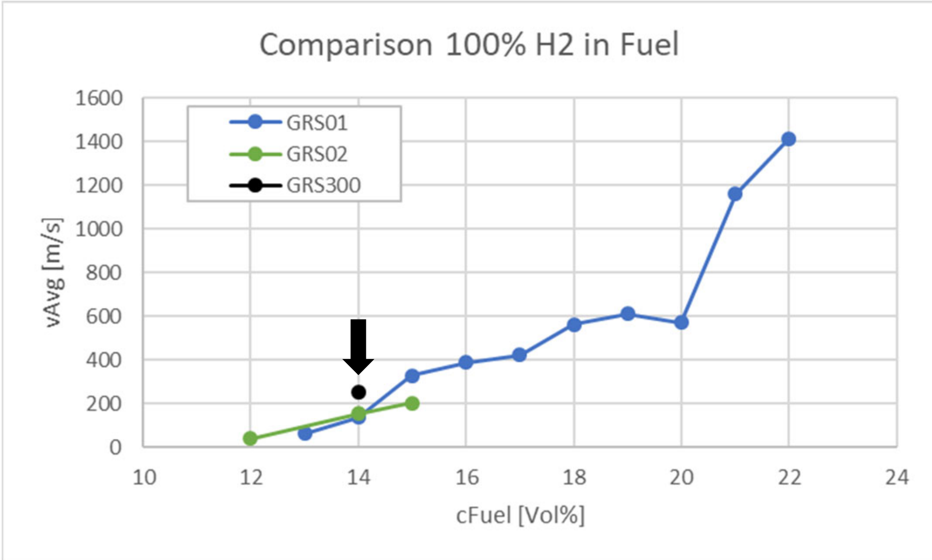


Experiments with homogeneous H_2-CO-air mixtures

Reference-Test (GRS300) in comparison with earlier experiments

- Series of **10** + **3** experiments with same channel-configuration and H_2-concentrations between 12 and 22 Vol% from the first two campaigns are available:



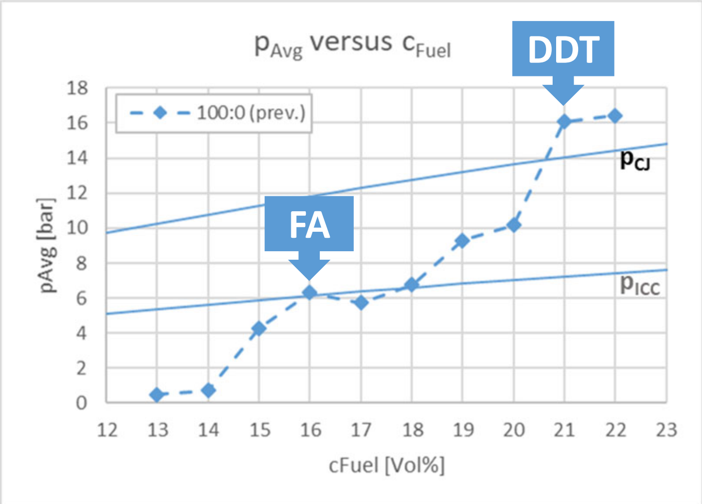


- Reference-Test GRS300 shows good agreement with existing data,

  ➔ Facility is in similar state as in previous series and results can be compared.

Experiments with homogeneous H_2-CO-air mixtures

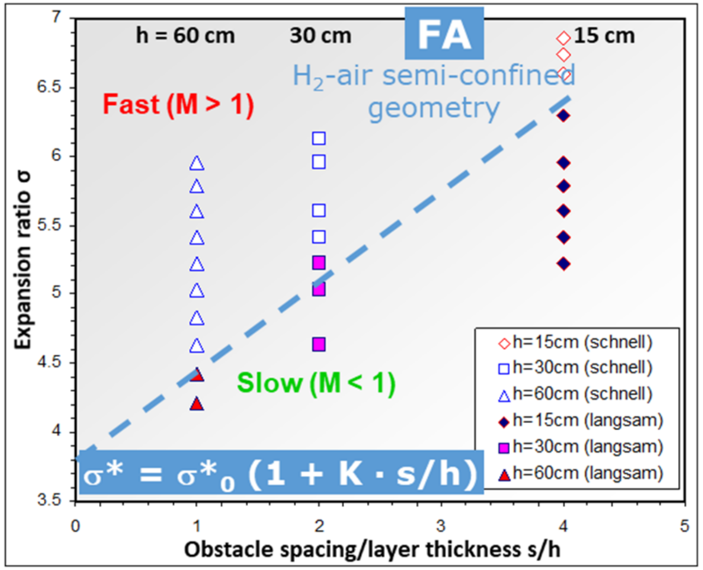
Summary of experiments with homogeneous H_2-air mixtures

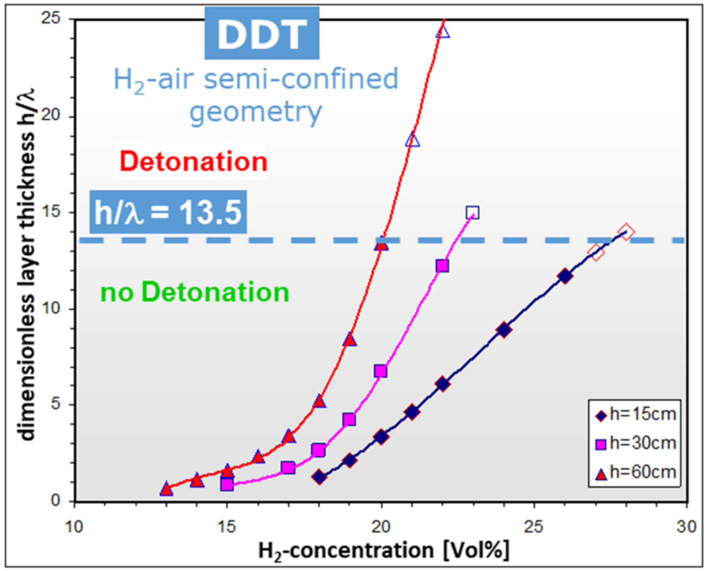


- To identify experiments with FA to sonic speed or DDT, averaged measured pressures (and velocities) in the last 3 m of the channel were compared with theoretical values (CANTERA):
  - p_{ICC}: adiabatic isochoric complete combustion pressure,
  - p_{CJ}: theoretical detonation overpressure.

- Experiments were then divided in groups with or without FA or DDT and plotted to derive criteria graphically.

In channel used:
K = 0.175; s = h = 0.6 m





Experiments with homogeneous H_2-CO-air mixtures

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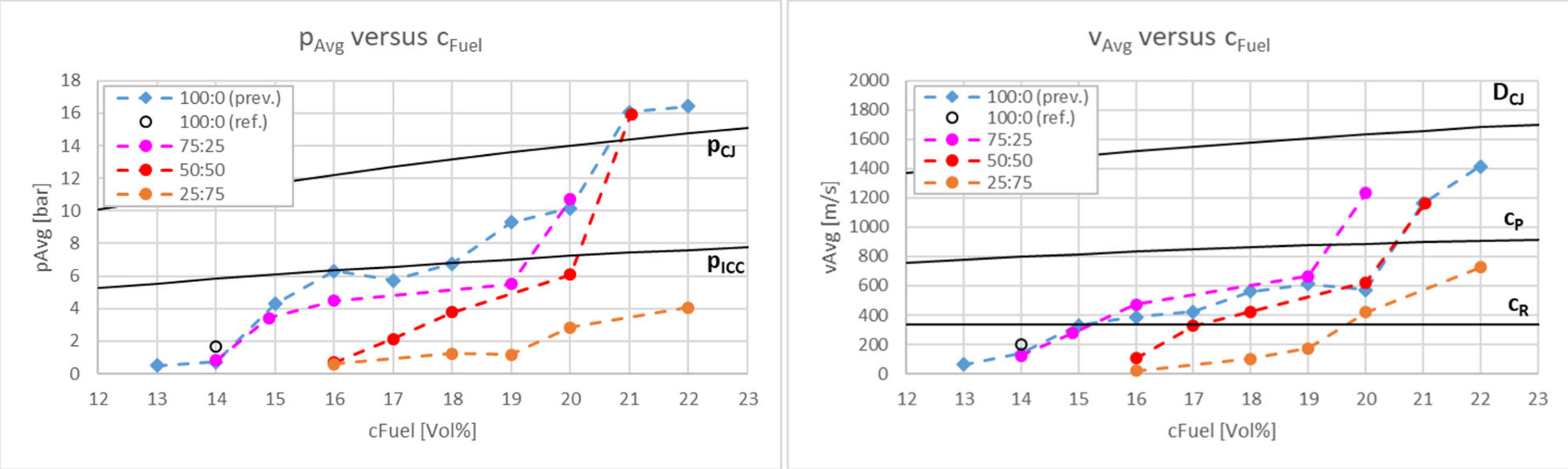
Summary of experiments with homogeneous H_2-CO-air mixtures



Combustion properties calculated with CANTERA for H_2/CO mixtures (50/50)

- Velocity deficit due to small gap in obstacles (< 3 λ) and quenching of detonation.

- With a CO-fraction of 25 Vol% in the fuel the combustion behavior is similar to “pure” H_2-air mixtures, although it leads to slightly lower overpressure values,
- Further replacement of H_2 by CO leads to:
  - Shift of transition to fast deflagration to higher fuel-concentrations,
  - DDT at similar fuel concentration for (100/0), (75/25) and (50/50), but higher concentrations for (25/75).

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Experiments with homogeneous H_2-CO-air mixtures

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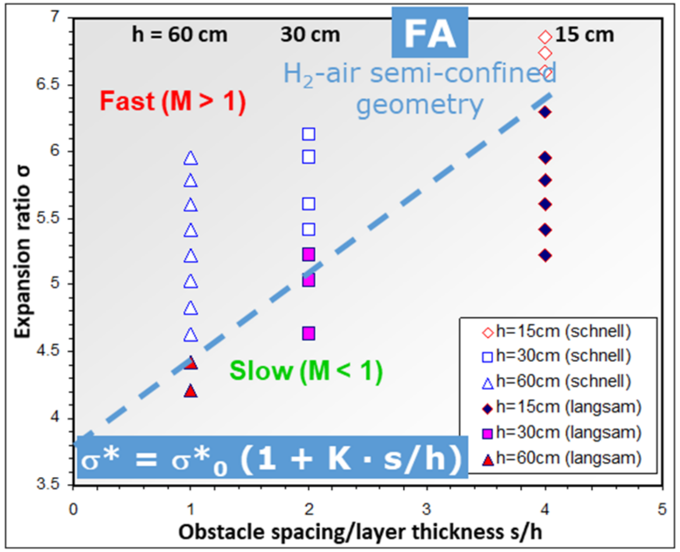
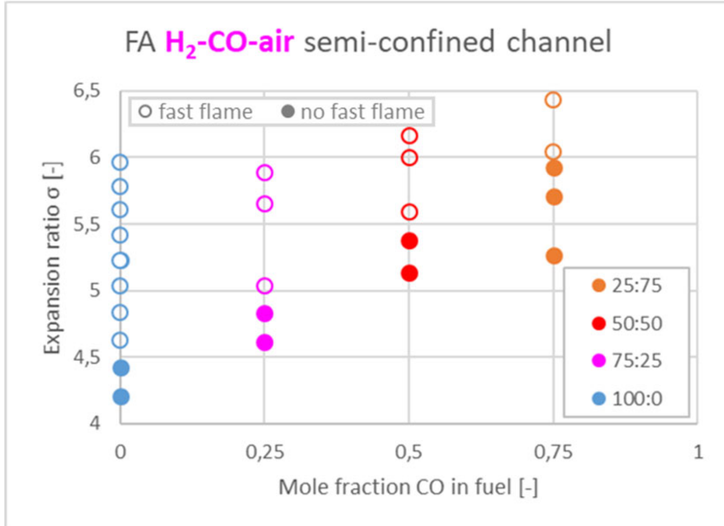
FA in homogeneous H_2-air mixtures and H_2-CO-air mixtures

- Expansion ratio σ (= ρ_R/ρ_P) of mixture was identified earlier as potential for effective FA to sonic speed, so experiments were plotted as expansion ratio over geometrical parameters.



- Blue line separates experiments with and without FA,
- Critical expansion ratio σ* for FA in H_2-air mixtures in semi-confined geometries depends on σ^*_0 for closed tubes and channel-geometry, especially vent ratio.

In channel used:
K = 0.175; s = h = 0.6 m



Same channel ➔ K = 0.175; s = h = 0.6 m

- Similar approach for experiments with H_2-CO-air mixtures in same semi-confined geometry by extending the equation to 2 fuels and weighing them according to their molar fraction in the fuel:

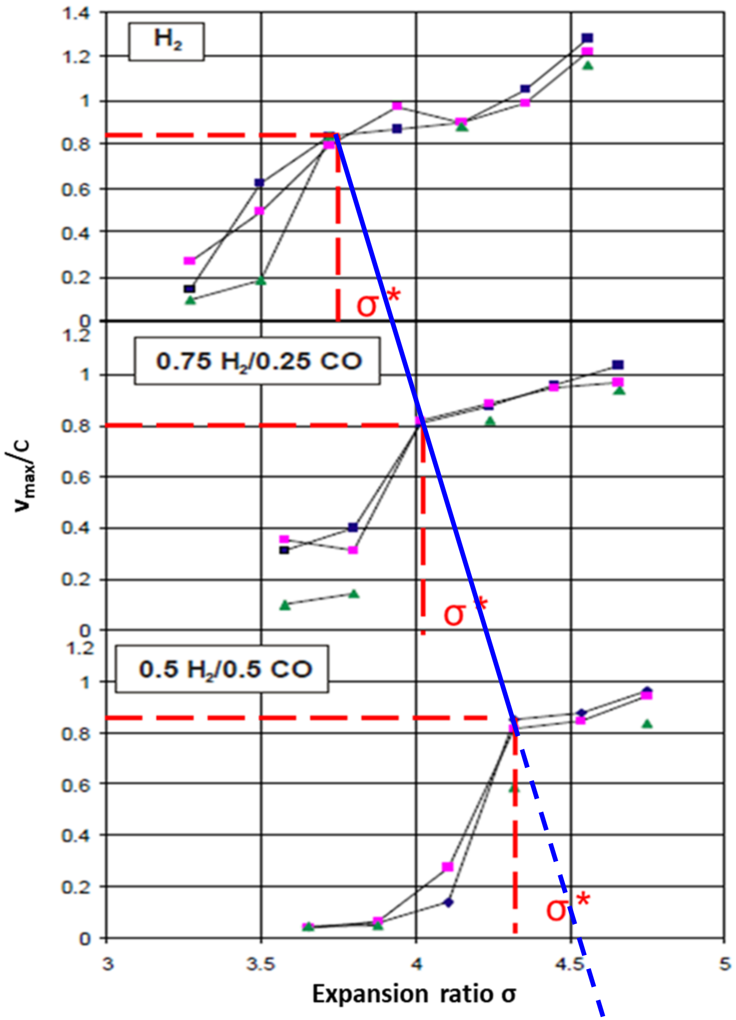
$$\sigma^* = [H_2] \cdot \sigma^*_0(H_2) \cdot (1 + K \cdot s/h) + [CO] \cdot \sigma^*_0(CO) \cdot (1 + K \cdot s/h)$$

- **But critical expansion ratio for CO-air mixtures in closed geometries is unknown.**

Experiments with homogeneous H_2-CO-air mixtures

FA in homogeneous H_2-CO-air mixtures

- Previous work with **closed** rectangular channel [1],
- In this campaign only the limited range of c_{Fuel} = 9 - 15 Vol% was investigated for H_2/CO-ratios of 100/0, 75/25 and 50/50,
- Interpretation of all measured maximum flame velocities for H_2-CO-air mixtures vs expansion ratio of the fuel gas σ shows systematic increase in the critical expansion ratio σ* with increasing CO content,
- Critical expansion ratio for FA is reached at $v_{max}/c \approx 0.8$ (v_{max}: maximum flame speed, c: speed of sound in burned gas),
- Using this data $\sigma^*_0 \approx 4.65$ for pure CO as fuel is extrapolated.



[1] Veser, A., Stern, G., Grune, J., Breitung, W., Burgeht, B. CO-H2-air combustion tests in the FZK-7m-tube Programm Nukleare Sicherheitsforschung. Jahresbericht 2001. Teil1 Wissenschaftliche Berichte, FZKA-6741 (Juni 2002), S.6-14

Experiments with homogeneous H_2-CO-air mixtures

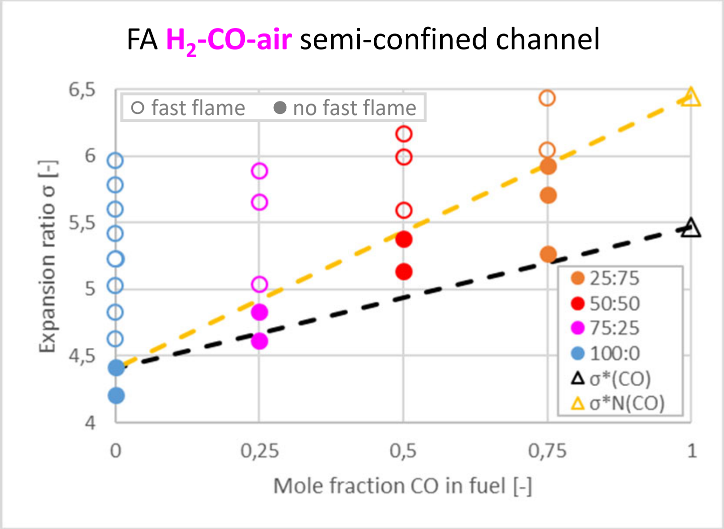
FA in homogeneous H_2-CO-air mixtures

- Using $\sigma^*_0(CO) = 4.65$, the channel specific values of K = 0.175 and s = h = 0.6 m and equation

$$\sigma^* = [H_2] \cdot \sigma^*_0(H_2) \cdot (1 + K \cdot s/h) + [CO] \cdot \sigma^*_0(CO) \cdot (1 + K \cdot s/h)$$

  a value of $\sigma^* = 5.46$ is calculated for [CO] = 1.

- Equation is accurate for mixtures without CO, but overestimates potential for FA to sonic speed with increasing CO-fraction in fuel.
- Discrepancy grows almost linearly with increasing CO-fraction, so a pre-factor "a", containing fuel specific properties, is added.
- Equation is accurate for H_2-air mixtures, so pre-factor $a(H_2) = 1$.
- Graphical solution for determination of pre-factor a(CO): value for critical expansion ratio of CO-air mixtures in semi-confined channel is set to be $\sigma^*(CO) \approx 6.45$ in the graph.



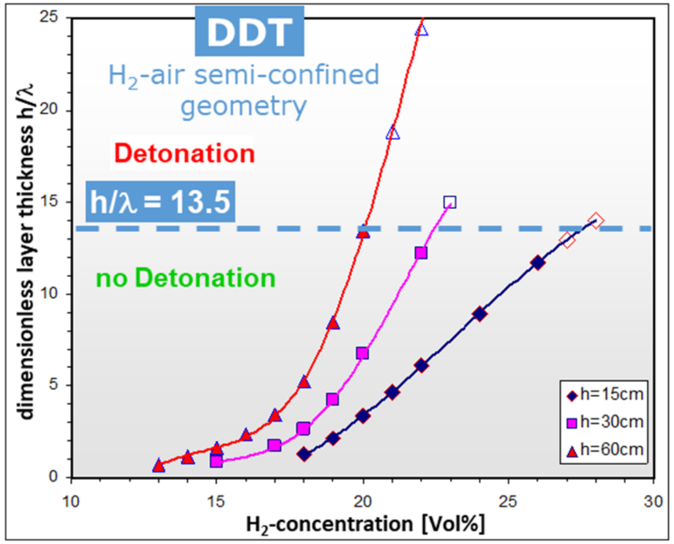
- Assumption yields pre-factor a(CO) = 1.18, which generates values for σ* that correspond with the dashed yellow line that separates experiments with FA from experiments without FA.

$$\sigma^*_N = a(H_2) \cdot [H_2] \cdot \sigma^*_0(H_2) \cdot (1 + K \cdot s/h) + a(CO) \cdot [CO] \cdot \sigma^*_0(CO) \cdot (1 + K \cdot s/h)$$

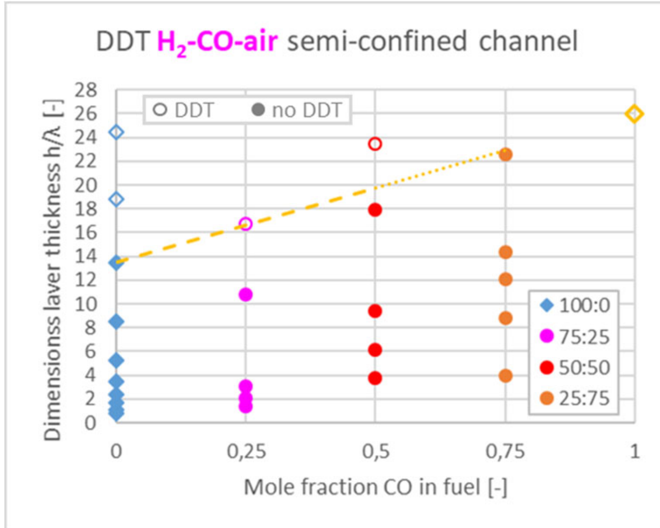
Experiments with homogeneous H_2-CO-air mixtures

DDT in homogeneous H_2-air mixtures and H_2-CO-air mixtures

- In similar manner a criterion for the onset of DDT in H_2-air mixtures in semi-confined geometries was derived in the previous projects:



- Blue line again separates experiments with and without DDT,
- Onset of DDT in H_2-air mixtures is mainly dependent on mixture reactivity (λ) and critical length (h).
- Similar approach for experiments with H_2-CO-air mixtures in same semi-confined geometry,



- Again extension of equation to 2 fuels that are weighted according to their molar fraction in the fuel:

$$h/\lambda = [H_2] \cdot h/\lambda(H_2) + [CO] \cdot h/\lambda(CO)$$

- **Again h/λ for CO-air mixtures in semi-confined geometries is unknown,**
- **Assumption of $h/\lambda(CO) = 26$ allows to separate experiments with and without DDT.**

Experiments with homogeneous mixtures

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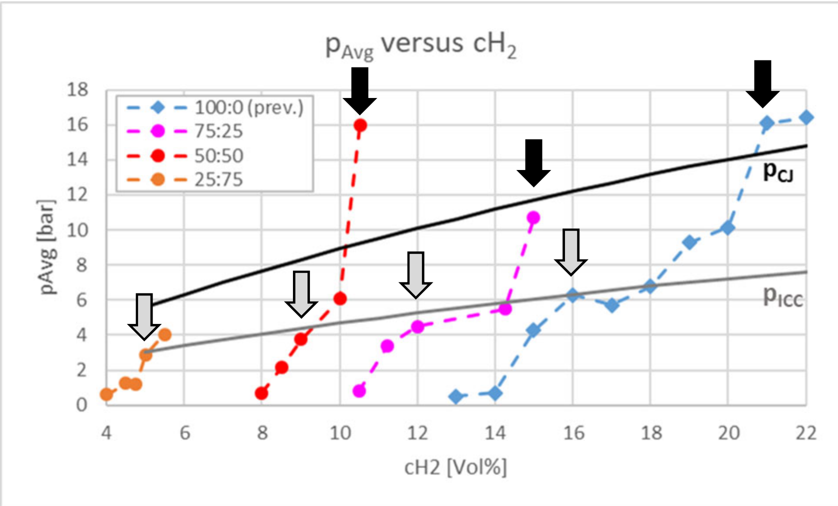
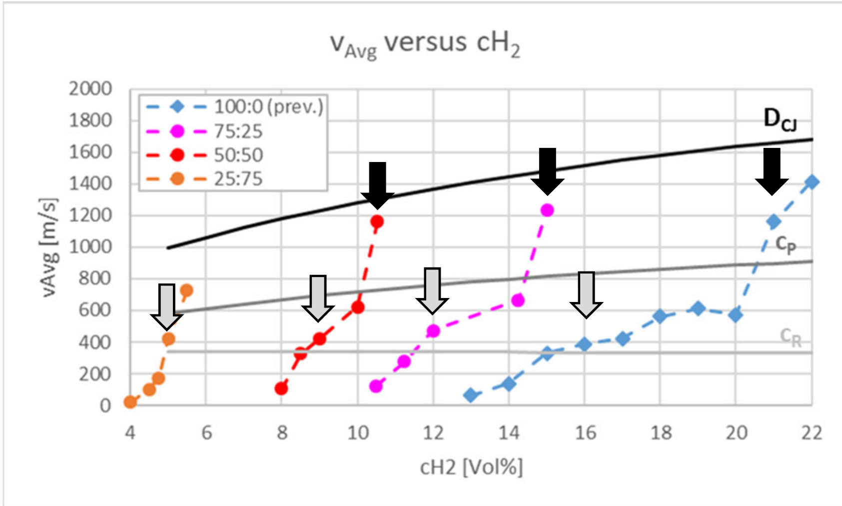
Summary of experiments with homogeneous H_2-CO-air mixtures

- Previous slides covered scenario where H_2 is replaced by CO, addition of CO to H_2 looks different:





Combustion properties calculated with CANTERA for H_2/CO mixtures (50/50)

- **FA** becomes possible at cH_2 of
  - 12 Vol% (for 75/25 mixtures),
  - 9 Vol% (for 50/50 mixtures) or
  - 5 Vol% (for 25/75 mixtures)

  if respective amount of CO is added.

- **DDT** becomes possible at cH_2 of
  - 15 Vol% (for 75/25 mixtures) or
  - 10.5 Vol% (for 50/50 mixtures)

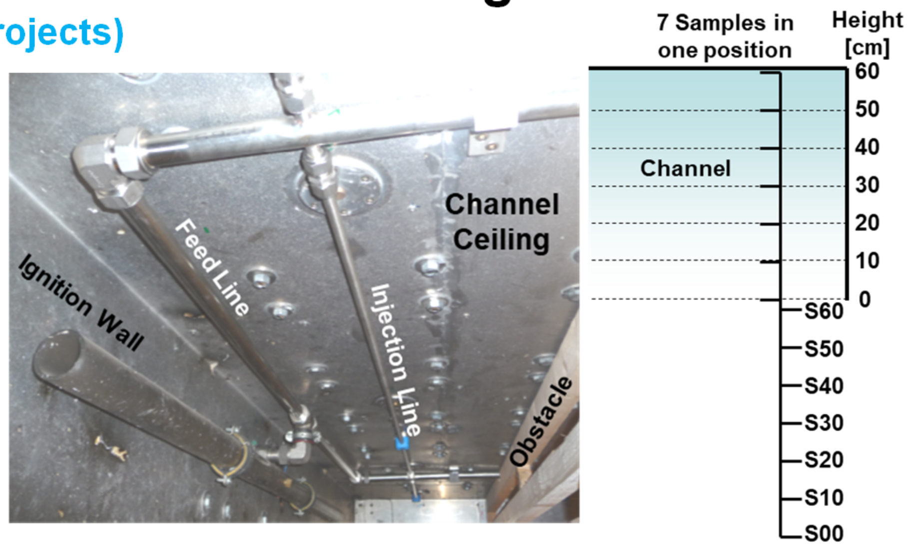
  if respective amount of CO is added.

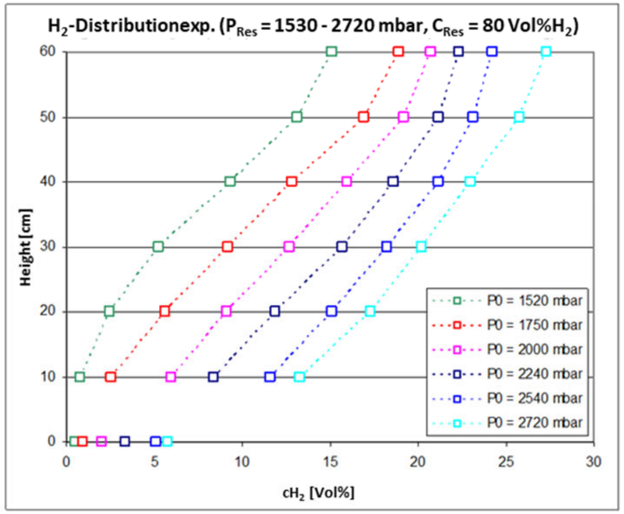
Generation of H_2-CO-air gradient-mixtures

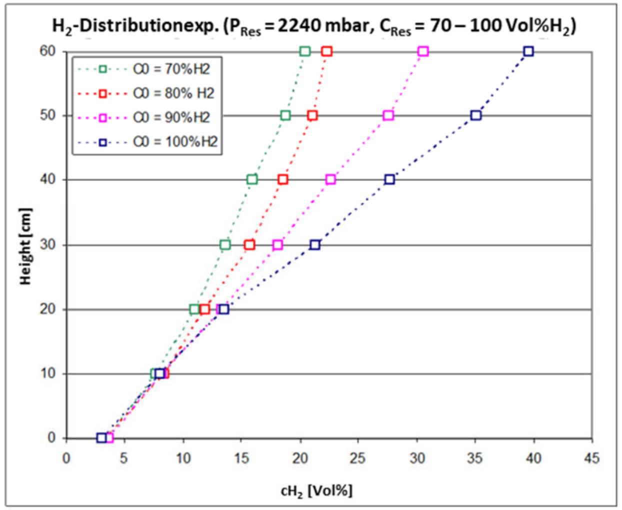
Generation of H_2-air mixtures with defined concentration gradients

(Method of previous projects)

- H_2-concentration gradients generated reproducibly by injecting H_2-air mixtures with **defined composition (C_{Res})** from a reservoir with **defined initial pressure (p_{Res})** into the channel until pRes = 1050 mbar.







- Increasing reservoir-pressure „shifts“ gradients to higher concentrations,
- Increasing H_2-fraction in reservoir leads to higher gradient-slope (cH_2max – cH_2min),
- Lower gradient slope yields larger flammable regions in channel.

Generation of H_2-CO-air gradient-mixtures

Generation and characterization of H_2-CO-air gradient-mixtures

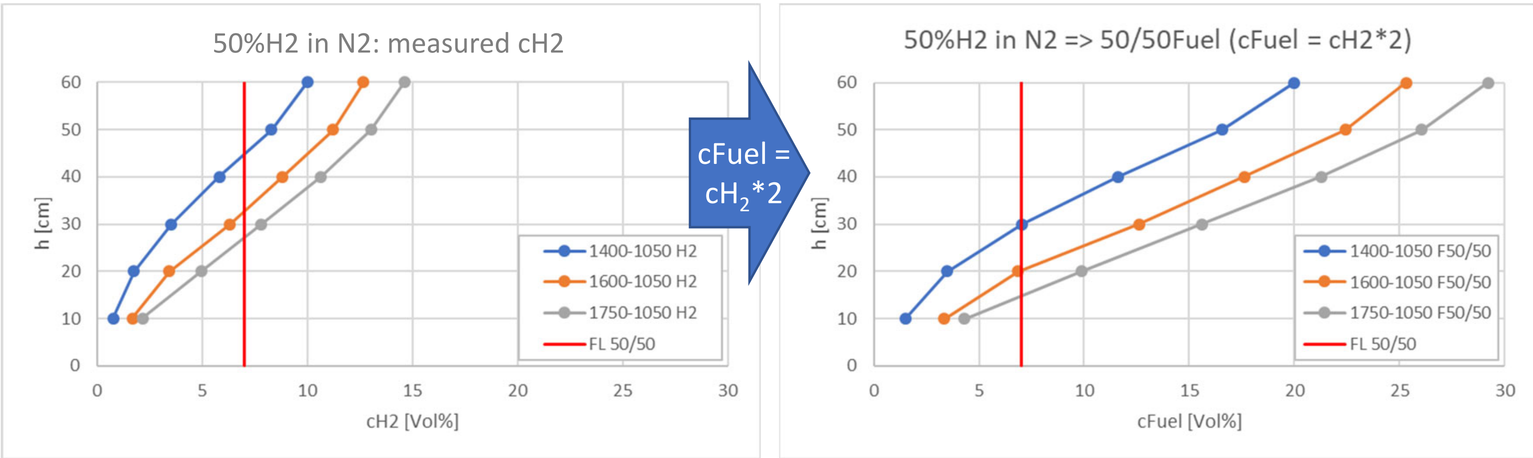
- For experiments with **H_2-CO mixtures** same injection system as for **H_2-air mixtures** is used, so
  - Proof of homogeneity over entire channel surface not explicitly provided again.
  - All distribution tests performed with 3 sampling positions, located in several different positions in channel.
- In distribution experiments with **H_2-CO mixtures** large CO-quantities are released, which must be safely disposed of after gradient formation has been measured,
- CO is very toxic (disposal is very lengthy since purging of safety-vessel with air takes approx. 1 day until it can be re-entered) and comparatively expensive.
- CO has same molecular weight as N_2 and therefore has almost identical flow properties,

➔ So first distribution tests were carried out with **H_2-N_2 mixtures**,
which have very similar flow properties as **H_2-CO-air mixtures**,
but are not flammable and also non-toxic.

Generation and characterization of H_2-CO-air gradient-mixtures

Step 1: Experiments with H_2-N_2 mixtures

- For generation of gradients with fuel gas ratio H_2/CO 50/50 distribution experiments with 50% H_2 in N_2 were performed (N_2 represents CO-fraction in later test mixture).



- Analysis of gradients produced this way (cFuel = measured cH_2*2) shows that gradients are too steep for planned investigations: In uppermost measuring point stoichiometric mixture is measured, while mixture not yet flammable at lowest measuring point.

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Generation of H_2-CO-air gradient-mixtures

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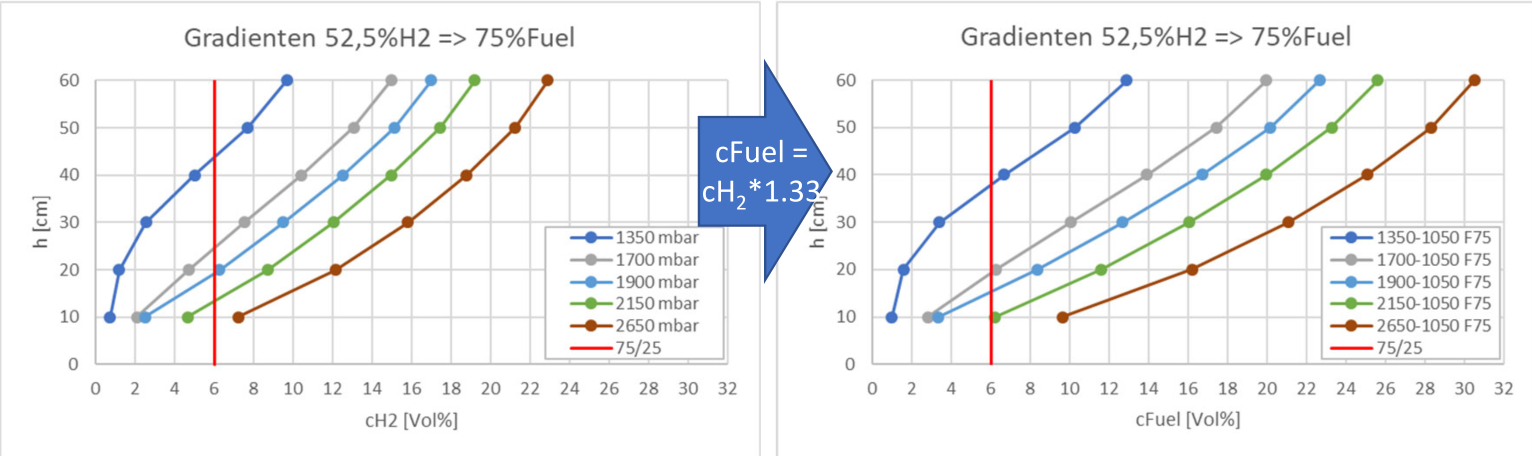
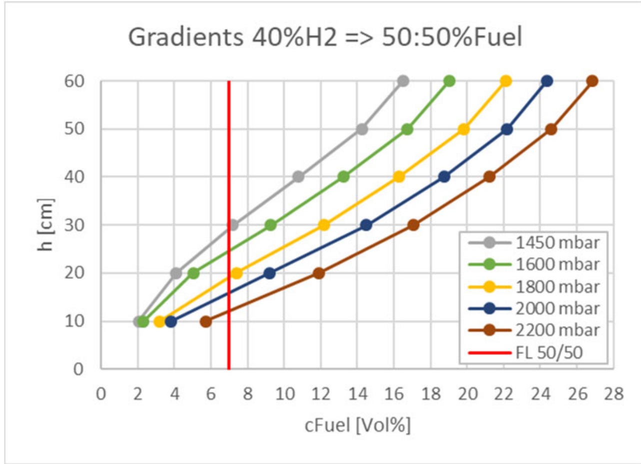
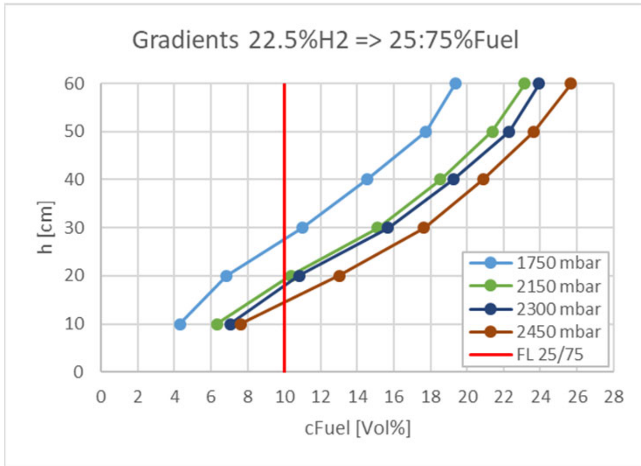
Generation and characterization of H_2-CO-air gradient-mixtures

Step 1: Experiments with H_2-N_2 mixtures

- Air in reservoir mixture reduces gradient steepness.







- Reservoir composition 52.5%H_2 in N_2 to model H_2:CO-mixtures 75:25 (N_2-fraction representing 17.5%CO and 30%air, cFuel = cH_2*1.333),
- Calculated gradients flammable in lower channel heights,
- Similar approaches also for other fuel ratios H_2:CO of 50:50 and 25:75 (with cH_2 40% and 22.5% in reservoir).

Generation and characterization of H_2-CO-air gradient-mixtures

Step 2: Conversion of the results to H_2-CO-air mixtures

After investigating conditions for generation of gradient mixtures with H_2-N_2 mixtures, results obtained were verified with H_2-CO-air mixtures.

But for reasons of time and cost only random sampling is possible, since:

- Only 2 CO sensors available for measuring gas samples,
- Response time CO sensors ($\approx$ 20 s) significantly longer than for H_2-sensors (< 5 s),
- CO sensors very pressure sensitive (900 mbar < p < 1200 mbar), so sampling cylinders cannot be used (evacuation due to gas extraction during analysis),
- Measurement must be permanent sampling over approx. 25 s per measuring point.

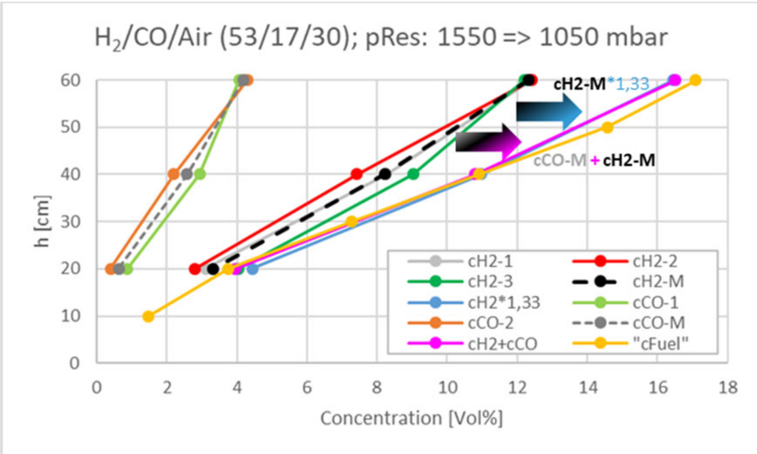
➔ Measurements only made in 3 (instead of 6) heights per measuring point because of influence on neighboring position due to permanent sampling, and unknown stability of gradients (> 3 minutes for 6 positions).

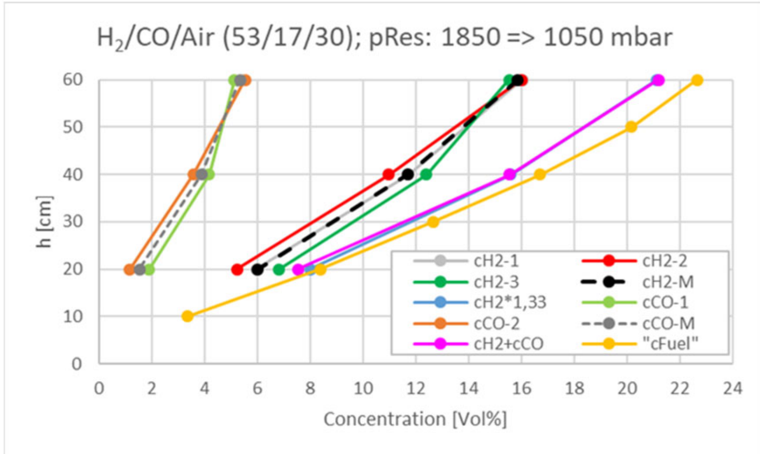
➔ Due to complex post-processing and purging of vessel test frequency reduced to less than 1 experiment per day when CO is used in test mixture.

Generation and characterization of H_2-CO-air gradient-mixtures

Step 2: Conversion of the results to H_2-CO-air mixtures

- Conversion for H_2:CO = 3:1 (75:25) (Reservoir: cH_2 = 52.5 vol%, cCO = 17.5 vol%, cAir = 30 vol%).



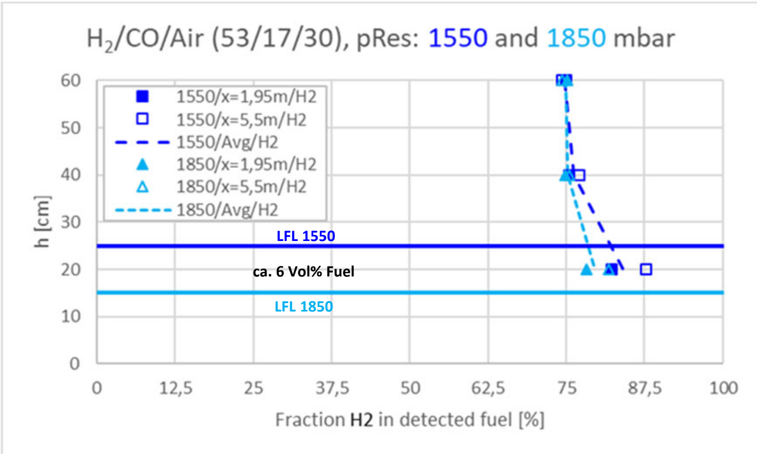


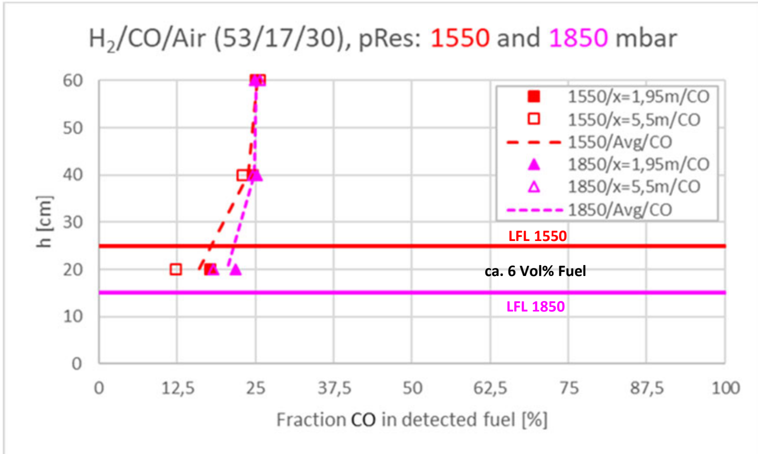
- H_2 and CO concentrations in different measuring positions show similar courses,
- Both calculated cFuel ***cH2-M*1.33*** and ***cCO+cH$_2$*** are almost equal,
- Comparison with **Pre-experiment** (N_2 instead of CO) shows good agreement, but for higher reservoir pressures values become slightly lower than calculated (right **Pre-experiment** started with slightly higher reservoir pressure (1900 mbar)).

Generation and characterization of H_2-CO-air gradient-mixtures

Step 2: Conversion of the results to H_2-CO-air mixtures

- Good result for mixture composition in upper half (H = 60, 40 cm) of channel,
- Lowest measuring point (H = 20 cm) shows strong deviation from initial composition (75:25), especially for lower reservoir pressures.



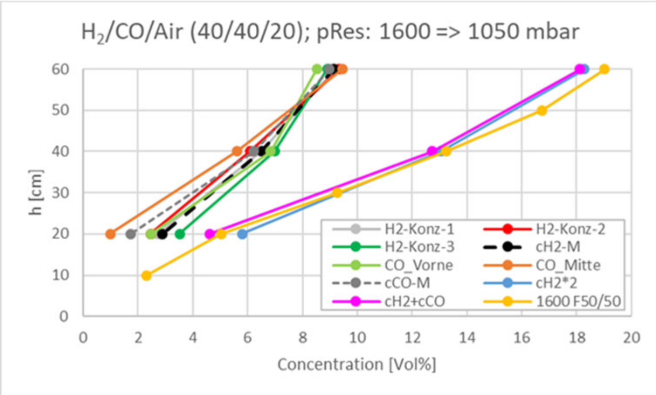


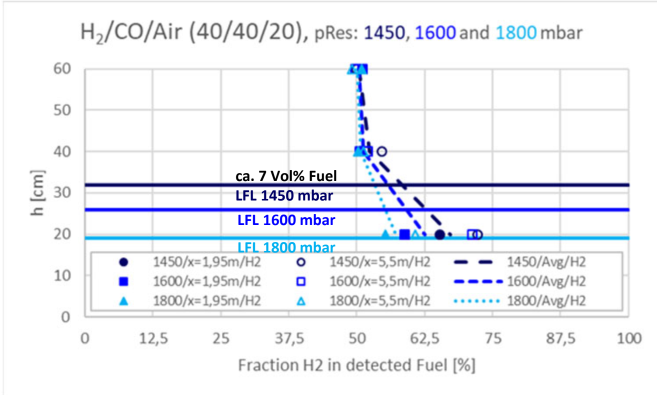
- But in this height measured cFuel is already below or close to LFL (ca. 6% fuel for this ratio) and measured cH_2 and cCO values in this position are very low (< 6 Vol% H_2 and < 2 Vol% CO) and thus these values show increasing measuring uncertainty.

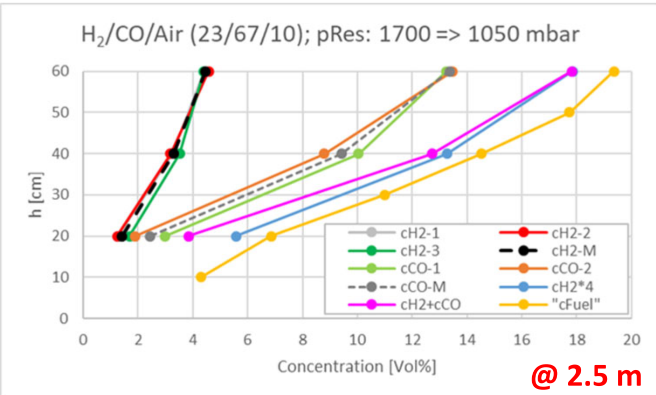
Generation and characterization of H_2-CO-air gradient-mixtures

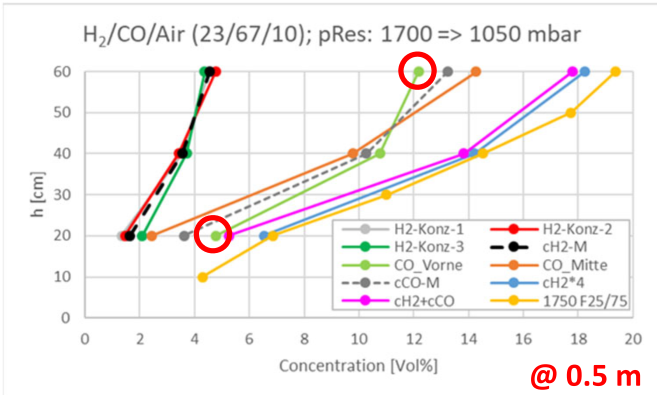
Step 2: Conversion of the results to H_2-CO-air mixtures

- Similar findings for other mixture compositions (H_2:CO = 50:50 or 25:75):









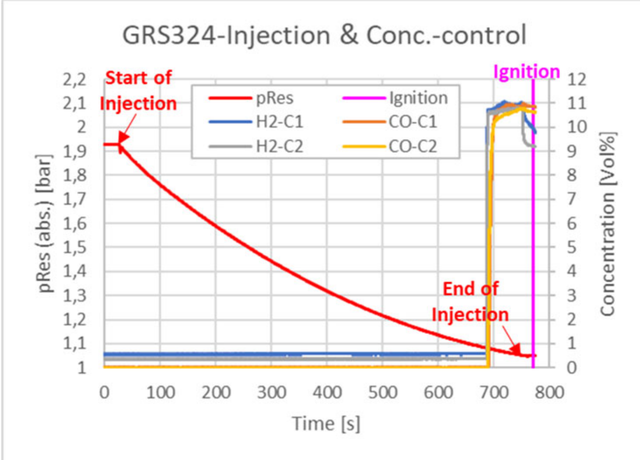
- But accuracy decreases with increasing CO-fraction …

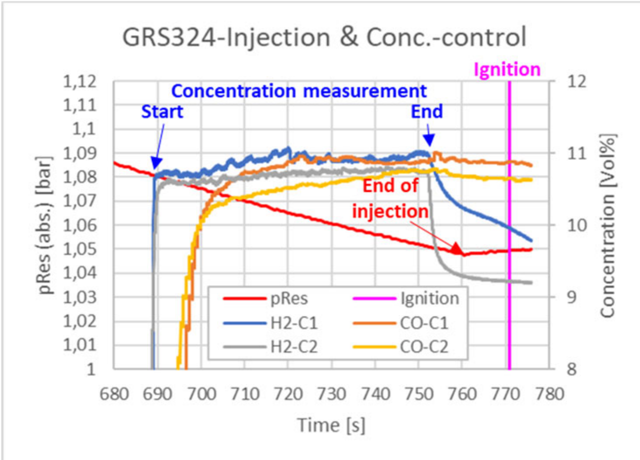
- … and also an untypical behavior for CO was observed for the CO-richest mixture when cCO is measured close to the ignition wall (< 2.5 m).

Experiments with H_2-CO-air gradient-mixtures

Test procedure for experiments with H_2-CO-air gradient-mixtures

- Prior to experiment gas flow with desired H_2-CO-air composition is generated using massflow-controllers (H_2-fraction measured constantly),
- When desired composition has established flow is directed into reservoir, which is then compressed to desired pressure.
- Gas sample from reservoir is taken and H_2-content is checked again.
- When facility is prepared and secured a computer controlled routine is started which opens valves to injection lines in channel and also closes them again at reservoir pressure 1050 mbar,
- At reservoir pressure 1080 mbar gas analysis is activated manually (cH_2 and cCO measured close to channel ceiling in 2 positions),
- 10 s after closure of injection valves the ignition device is activated and the data acquisition is triggered (0.5 s prior to ignition valves to the gas analysis are closed automatically, if still open).
- Mean concentration from measurements taken for c_{max} in evaluation.





Experiments with H_2-CO-air gradient-mixtures

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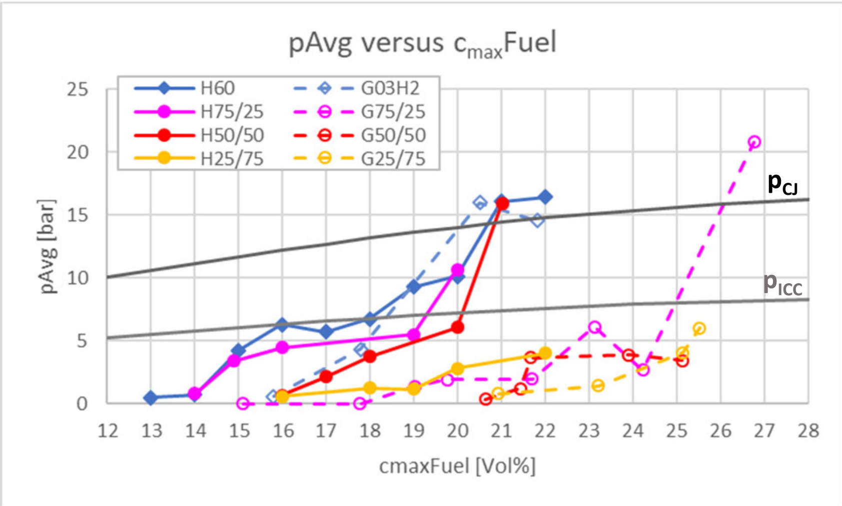
Ratio cH_2 / cCO	Experi-ment	Fuel {Vol%]	cH_2max [Vol%]	cCOmax [Vol%]	$V_{avg(End)}$ [m/s]	$P_{avg(End)}$ [bar]	σ [-]	λ [cm]
75 / 25	326	**15** (15.1)	**11.25** (11.2)	**3.75** (3.9)	-	-	4.885	23.0
	327	**18** (17.8)	**13.5** (13.2)	**4.5** (4.6)	24	-	5.449	6.93
	328	**19** (19.0)	**14.25** (14.2)	**4.75** (4.9)	99	1.41	5.706	4.28
	329	**20** (19.8)	**15.0** (14.7)	**5.0** (5.0)	392	1.93	5.821	3.49
	330	**22** (21.7)	**16.5** (16.2)	**5.5** (5.5)	516	1.99	6.192	2.21
	331	**23** (23.1)	**17.25** (17.3)	**5.75** (5.8)	565	6.15	6.433	1.76
	332	**24** (24.2)	**18.0** (18.1)	**6.0** (6.1)	711	2.70	6.611	1.54
	333	**27** (26.8)	**20.25** (19.9)	**6.75** (6.9)	1181	20.82	6.970	1.21
50 / 50	320	**17** (17.0)	**8.5** (8.5)	**8.5** (8.6)	-	-	5.404	7.90
	321	**19** (18.9)	**9.5** (9.3)	**9.5** (9.7)	18	-	5.790	4.07
	322	**20.5** (20.6)	**10.25** (10.2)	**10.25** (10.4)	46	0.39	6.093	2.73
	323	**21.5** (21.4)	**10.75** (10.6)	**10.75** (10.8)	262	1.23	6.238	2.37
	324	**22** (21.7)	**11.0** (10.8)	**11.0** (10.8)	464	3.67	6.272	2.29
	325	**24** (23.9)	**12.0** (11.8)	**12.0** (12.1)	550	3.89	6.652	1.67
	334	**25** (25.1)	**12.5** (12.5)	**12.5** (12.6)	624	3.48	6.831	1.48
25 / 75	316	**21** (20.9)	**5.25** (5.3)	**15.75** (15.6)	15	0.81	6.243	3.17
	317	**23** (23.2)	**5.75** (5.8)	**17.25** (17.4)	275	1.44	6.630	2.28
	319	**25** (25.1)	**6.25** (6.3)	**18.75** (18.8)	430	4.07	6.890	1.86
	318	**25.5** (25.5)	**6.38** (6.2)	**19.13** (19.3)	491	6.03	6.940	1.82

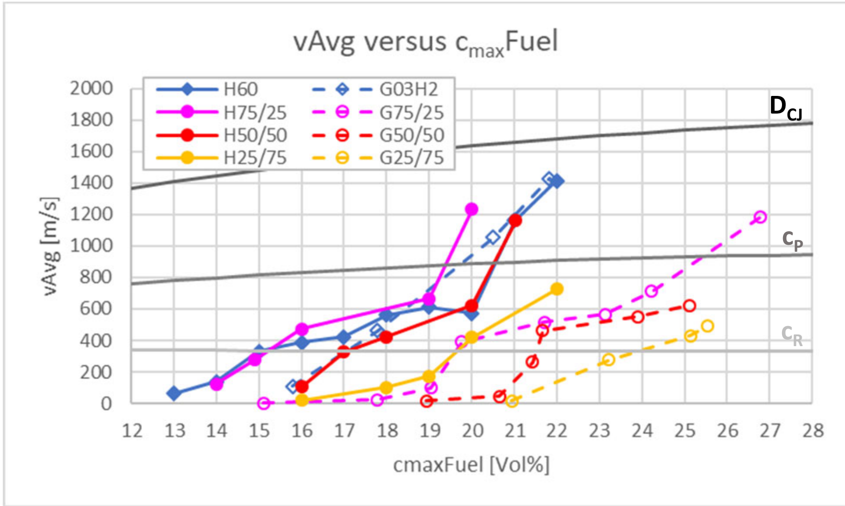
Test matrix

- Transitions from slow to fast deflagration determined.
- Transition to detonation determined only for (75/25).
- Detonation limit for (50/50) approached but not crossed due to lack of time and strong loads to facility.

Black: Slow (subsonic) combustion (M < 1)
Blue: Fast (sonic) combustion (M > 1)
Red: Quasi-detonation (v_{av} ~ (0.6-0.85)·D_{CJ}, M >> 1)

Summary of experiments with H_2-CO-air gradient-mixtures





- Again velocity deficit due to small gap in obstacles (< 3 λ) and quenching of detonation.

Combustion properties calculated with CANTERA for H_2/CO mixtures (50/50)

- Both blue curves for homogeneous and gradient **H_2-air mixtures** are very similar for c_{max} > 17 Vol% H_2
  ➔ „**Concept of Maximum Concentration**": **H_2-air gradient-mixture** of given c_{max} behaves similar as corresponding **homogeneous H_2-air mixture** of same concentration.
- But curves for **H_2-CO-air gradient-mixtures** are shifted to much higher concentrations compared to **homogeneous H_2-CO-air mixtures**, and so the transitions for FA and DDT are found at much higher concentrations.

Experiments with H_2-CO-air gradient-mixtures

FA in H_2-CO-air gradient-mixtures

- Same approach as for **homogeneous H_2-CO-air mixtures**, experiments plotted as expansion ratio over CO-fraction. Blue dots correspond to **H_2-air gradient mixtures** (Gradient slope -0.3 Vol%/cm).
- Black dashed line corresponds to 1st attempt to adapt FA-criterion to **homogeneous H_2-CO-air mixtures** (weighing of components):

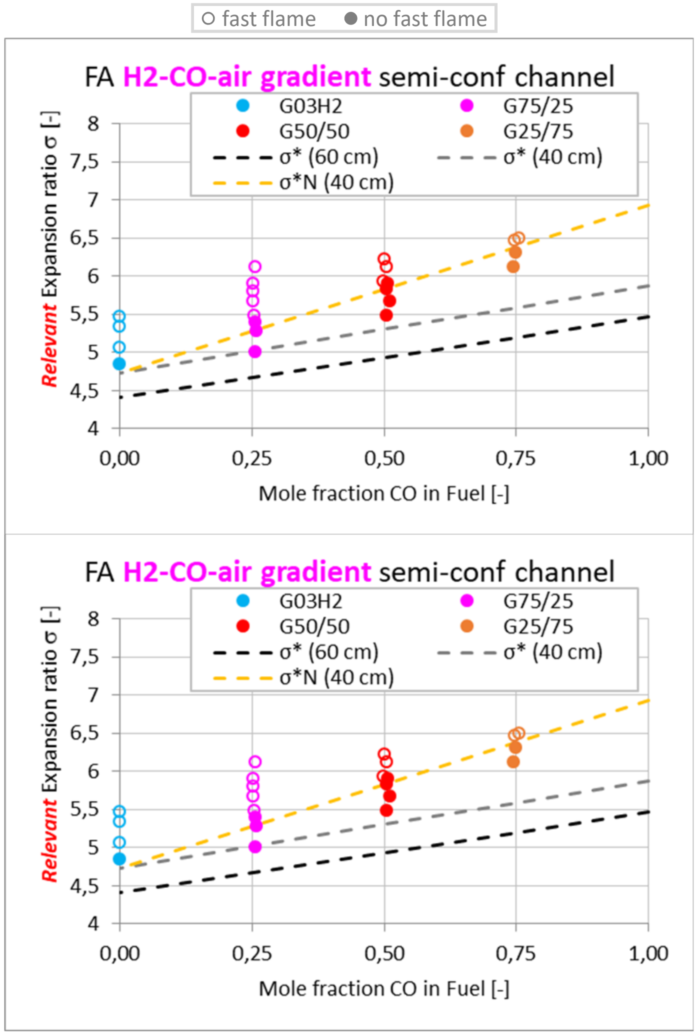
$$\sigma^* = [H_2] \cdot \sigma^*_0(H_2) \cdot (1 + K \cdot s/h) + [CO] \cdot \sigma^*_0(CO) \cdot (1 + K \cdot s/h)$$

- Grey dashed line corresponds to same FA-criterion, considering flammable height, as determined in bomb experiments (approx. 40 cm),
- Yellow dashed line corresponds to extended FA-criterion with pre-factors “a” for “accelerability” (and flammable height):

$$\sigma^*_N = a(H_2) \cdot [H_2] \cdot \sigma^*_0(H_2) \cdot (1 + K \cdot s/h) + a(CO) \cdot [CO] \cdot \sigma^*_0(CO) \cdot (1 + K \cdot s/h)$$

- **Final assumption:** only regions with fuel-concentrations higher than FA limit determined for **homogeneous H_2-CO-air mixtures** relevant. So relevant concentration introduced and used for calculation of σ.

$$c_{Relv} = (c_{max} + c_{FAL})/2$$



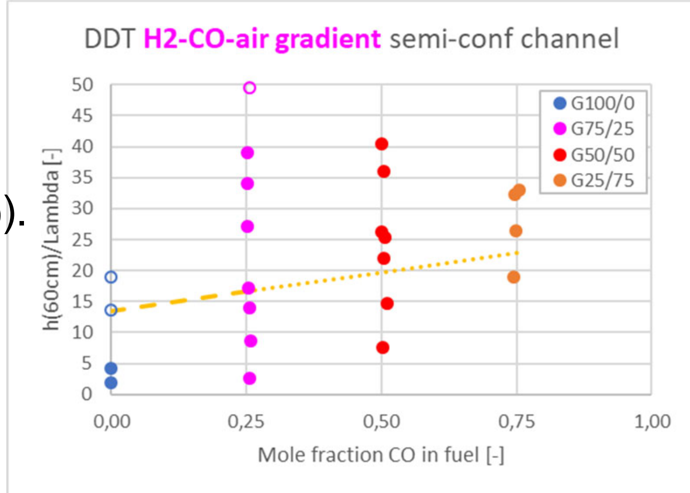
Experiments with H_2-CO-air gradient-mixtures

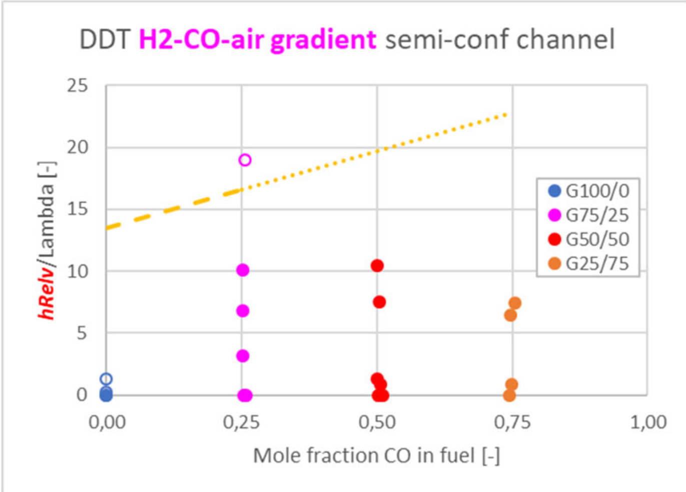
DDT in H_2-CO-air gradient-mixtures

- Same approach as for **homogeneous H_2-CO-air mixtures**, Experiments plotted as dimensionless layer thickness h/λ over mole fraction CO (Blue dots: **H_2-air gradient mixtures** (Gradient slope -0.3 Vol%/cm)).
- Yellow dashed and dotted line corresponds to 1st attempt to adapt DDT-criterion to **homogeneous H_2-CO mixtures** (weighing of components and assumption of h/λ(CO) = 26):

$$h/\lambda = [H_2] \cdot h/\lambda(H_2) + [CO] \cdot h/\lambda(CO)$$

- **Further assumptions:** only regions with fuel-concentrations higher than DDT limit determined for **homogeneous H_2-CO-air mixtures** relevant (assumption: DDT-limit for H_2/CO-ratio 25/75 is c_{Fuel} = 23 Vol%). So relevant height introduced and used for calculation of h/λ.
- Better agreement for single data point with DDT for **H_2-CO-air gradient-mixtures**, but no longer agreement for **H_2-air mixtures**!
- Too many assumptions and too few data points ➔ further investigation required for reliable criterion.





Summary

- The current work shows that CO-fractions in H_2-air mixtures can neither be neglected nor treated as H_2, since both, addition of CO and replacement of H_2 by CO in H_2-air mixtures has an influence on the combustion behavior of the mixture.
- In the current experimental program with **H_2-CO-air mixture** lavers in semi-confined geometries slow subsonic and fast sonic deflagrations as well as detonations were observed and the conditions for FA and DDT were determined and compared with the results of previous campaigns with **H_2-air mixture** layers in the same facility.
- The FA-criterion formulated earlier for **H_2-air mixtures** in semi-confined horizontal layers was extended to **homogeneous H_2-CO-air mixtures**, by weighing the influence of the two fuel components according to their molar fraction in the fuel and by introducing a pre-factor for every fuel component that incorporates all properties relevant for FA but not covered by the expansion ratio (e.g. kinetics, inhibitions, reaction pathways). For the extension of the criterion to **H_2-CO-air gradient-mixtures** a further extension using a relevant concentration was proposed.
- A similar approach for a modification of the existing criterion for DDT in semi-confined horizontal **H_2-air layers** was proposed for **homogeneous** and **inhomogeneus H_2-CO-air mixtures**, but this approach still lacks data on the detonation behavior of CO-rich mixtures for further development.

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Acknowledgements

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Thank you for your attention!

- We are very grateful to the project partners from TUM for fruitful discussions and support as well as the German Federal Ministry for Economic Affairs and Energy (BMWi) for funding (Project No. 1501545B) of this work.

Federal Ministry for Economic Affairs and Energy