



Development of Heating Technologies for the
Efficient Renewable Energy Consumption of
CO₂-Neutral Downstream-Processes

Deliverable 4.2

about the laboratory descaling tests at BFI

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1. Abstract

Descaling tests were conducted on three steel grades - ADI1, ADI3, and FER 1 - with the aim of determining whether and to what extent a change in possible future carbon free furnace operations increases the risk of quality losses, and what adjustments to the system could help mitigate that risk.

It was found that different steels react with varying degrees of sensitivity to such process changes.

A first series of experiments, comparing the different furnace operating modes directly, showed that steels with a low alloy content are not expected to descale any worse in future, whereas higher-alloy steel grades, which are already difficult to descale, could react sensitively to an increase in hydrogen content in the fuel gas.

In a second series of experiments, an attempt was made to derive a multi-parameter function to describe the residual scale coverage as a function of the descaling parameters and furnace operating modes. It was found that adding hydrogen to the combustion gas tends to result in poorer descaling results. However, it was not possible to derive a plausible function using linear regression. A better function could be derived in future using a Generalised Linear Model.

2. Introduction

The possible ways of decarbonising reheating processes are:

- 1) replacing natural gas (NG) with hydrogen (H_2) as a fuel gas,
- 2) (partial) electrification,
- 3) or a combination of both.

All variants change the reheating process in such a way that a reduction in descaling quality is to be expected. In addition to the altered heat transfer mechanisms resulting from changes in flow and radiation properties within the furnace chamber, the following phenomena are particularly significant:

- a) A higher water vapour content in the furnace chamber increases the plasticity of wustite, reduces the thermal shock effect and consequently leads to more strongly adhering scale and a reduction in descaling efficiency
- b) In furnace atmospheres rich in water vapour and free of carbon dioxide, thicker scale layers with altered morphology are formed, which can influence crack growth.
- c) Altered time-temperature profiles lead to changes in scale growth rates, which in turn affect the stress relaxation capacity, a factor that could have an influence on the thermal shock behaviour.

Deliverable D4.2 examines whether and to what extent these assumptions need to be taken into account for various production and descaling processes.

3. Background

For so-called high pressure water descaling system with a fixed spray bar arrangement, descaling is generally carried out by means of four mechanisms [1]:

1. Kinetic energy: The kinetic energy of the water deforms and/or shatters the scale (compare **Figure 1**).

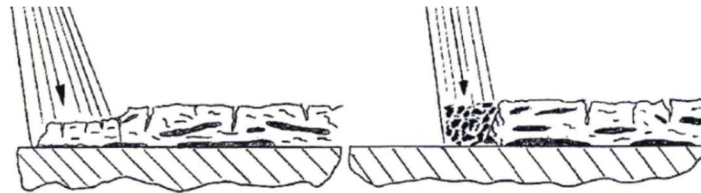


FIGURE 1: MECHANISM OF DEFORMATION (LEFT) AND FRACTURE (RIGHT) OF THE SCALE BASED ON THE KINETIC ENERGY OF THE WATER JET

2. Cooling: The different rates of thermal expansion of scale and steel generate shear stresses at the interface, causing the scale to lose its adhesion (compare **Figure 2**).

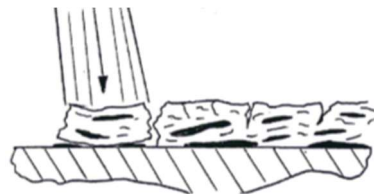


FIGURE 2: MECHANISM OF DELAMINATION DUE TO COOLING STRESSES

3. Evaporation: The water that penetrates the cracks and pores of the scale evaporates suddenly. The resulting increase in volume causes the scale to burst apart (compare **Figure 3**).

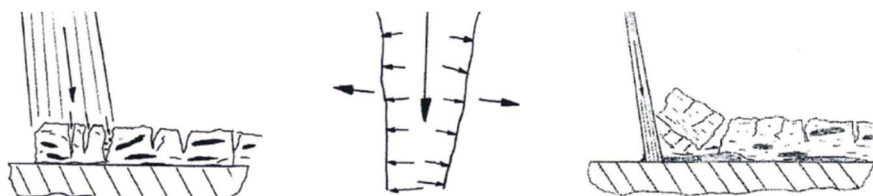


FIGURE 3: MECHANISM OF THE SUDDEN INCREASE IN THE VOLUME OF WATER DUE TO EVAPORATION

4. Wash away: Scale particles and flakes are washed away by water.

Figure 4 shows a schematic diagram of a spray bar assembly, including the general control variables.

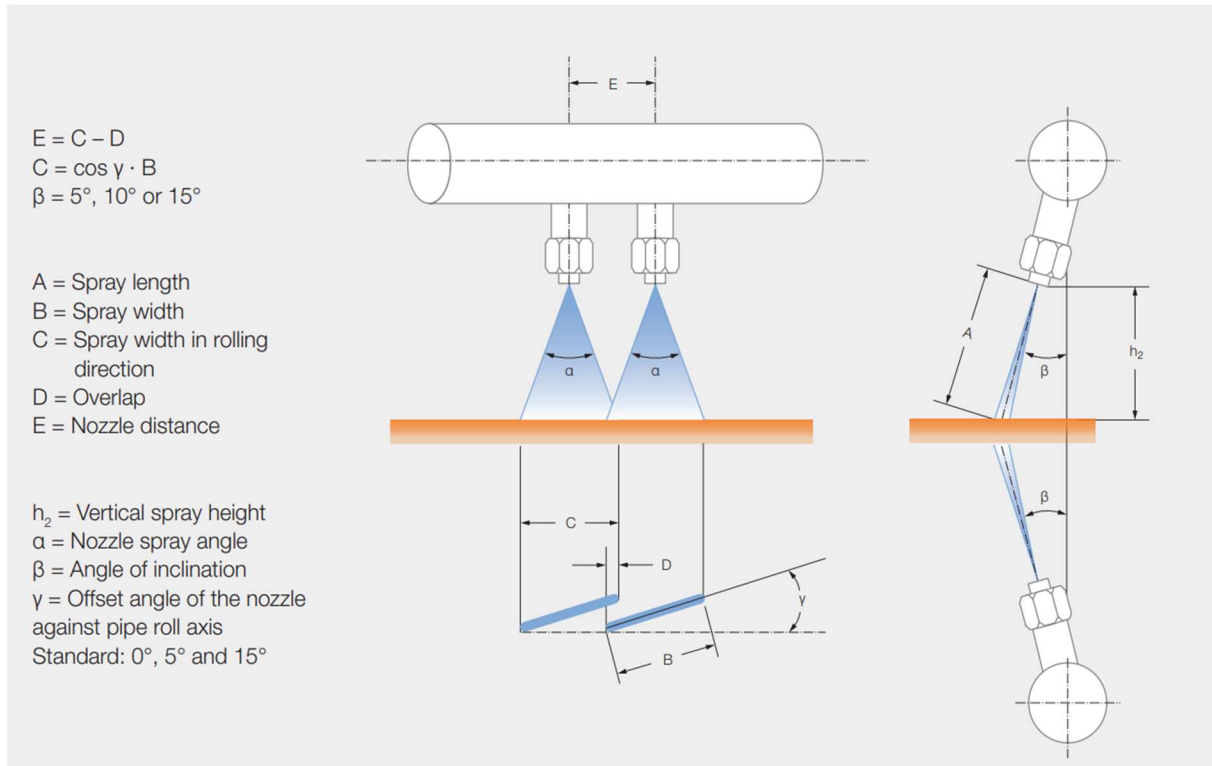


FIGURE 4: KEY PARAMETERS OF NOZZLE ARRANGEMENTS IN A SPRAY BAR, COMPARE [2]

In addition to the nozzle arrangement and type, other parameters specified by the manufacturer influence the descaling performance [3], such as:

- the vertical spray distance h_2 [mm]
- the pressure p [bar]
- the volumetric flow rate ($\dot{V}$) [l/s]
- the nozzle spray angle α [°]
- the inclination angle β [°]
- the offset angle of the nozzle γ [°]
- the product velocity v [m/s]

These parameters are determining the:

- force F_l [N] with which the jet strikes the scale:
 - general calculation based on the law of conservation of momentum (**eq. 1**), with density of the fluid ρ [kg/m³] and gravity constant g [m / s²],
 - calculation taking into account an atmospheric deceleration constant c_v [–] (depending on h_2 , $c_v \approx 1$) and a flow constant c_f [m * s / √kg] ($c_f = 0.85$) (**eq. 2**),

- the impact pressure IP [MPa] (**eq. 3**), the ratio of force to the water exposed area A_I [mm²] (**eq. 4**), where B [m] and d [m] are the width and thickness of the jet at the surface of the material to be treated and with jet thickness angle ϕ [°],
- the specific water impingement SWI [l/m²] (**eq. 5**), which takes into account the residence time of the scale beneath the spray vane, and
- the descaling energy DE [J/m²] (**eq. 6**), a parameter describing the descaling performance.

$$\text{eq. 1} \quad F = \frac{d}{dt}(m \cdot v) = \dot{m}v + m\dot{v} = 0 + \dot{V} * \sqrt{2 * p * \rho} = F_{I(1)} \quad [3]$$

$$\begin{aligned} & \text{with } F_{I(2)} = \rho * \dot{V} * c_v * v_f \\ \text{eq. 2} \quad & \text{and } v_f = c_f * \sqrt{2 * g * p * 10,2} \quad [3] \\ & \text{follows } F_{I(2)} = \rho * \dot{V} * c_v * c_f * \sqrt{2 * g * p * 10,2} \end{aligned}$$

$$\text{eq. 3} \quad IP = \frac{F}{A} = \frac{F_I}{A_I} \quad [3]$$

$$\begin{aligned} & \text{from } B = \tan\left(\frac{\alpha}{2}\right) * \frac{2 * h_2}{\cos(\beta)} \\ \text{eq. 4} \quad & \text{and } d = \tan\left(\frac{\phi}{2}\right) * \frac{2 * h_2}{\cos(\beta)} \quad [3] \\ & \text{follows } A_I = \frac{4 * h_2^2}{\cos^2(\beta)} * \tan\left(\frac{\alpha}{2}\right) * \tan\left(\frac{\phi}{2}\right) \end{aligned}$$

$$\text{eq. 5} \quad SWI = \frac{\dot{V}}{v * d} \quad [3]$$

$$\text{eq. 6} \quad DE = IP * SWI \quad [3]$$

4. Considered production processes

4.1 Slabs and Billets

At ADI site, slabs of size approximately $6,000 - 12,500 \times 940 - 700 \times 230 - 245 \text{ mm}^3$ are reheated in a coke oven gas (COG)-fired furnace before hot rolling. In E-ECO Downstream two steel grades are considered regarding descaling, see **Figure 6** to **Figure 6** and **Table 1**.



FIGURE 5: DESCALING SAMPLES: ADI1



FIGURE 6: DESCALING SAMPLES: ADI3

At FER site, billets of size approximately $12,200 \times 150 \times 150 \text{ mm}^3$ are reheated in a NG fired furnace before hot rolling. In E-ECO Downstream one steel grade is considered regarding descaling, see **Figure 6** and **Table 1**.



FIGURE 7: DESCALING SAMPLES: FER1

TABLE 1: CONSIDERED STEEL GRADES

Internal name			ADI1	ADI3	FER
Feedstock type			slab		billet
Feedstock dimension	I	[mm]	6000 - 12,500		12,200
	w		1,000 - 1,700		150
	h		230 - 245		150
Surface state of feedstock		[-]	mill scale		mill scale
Steel grade		[-]	C-Mn steel	Micro alloyed steel	unalloyed low-carbon steel grade
Feedstock composition c_i	C	[%]	0.05 - 0.07	0.16 - 0.18	0,17 - 0.23
	Mn		0.30 - 0.40	1.0 - 0.15	0.30 - 0.60
	Al		0.03 - 0.06	0.02 - 0.06	-
	Nb		-	0.035 - 0.045	-

4.2 Reheating conditions

ADI's reheating furnaces use COG with varying fuel gas compositions (see **Table 2**). The products are heated from room temperature to approximately 1,200 °C within 180 minutes and held there for approximately 60 minutes (see **Figure 8**).

FER's reheating furnaces use NG. The products are heated from room temperature to approximately 1,200 °C within 150 minutes and held there for approximately 60 minutes (see **Figure 8**).

In both cases, ADI and FER, for the descaling tests, a 50 % H₂ enrichment of the fuel gas and 100 % hydrogen combustion are taken into account (see **Table 2**).

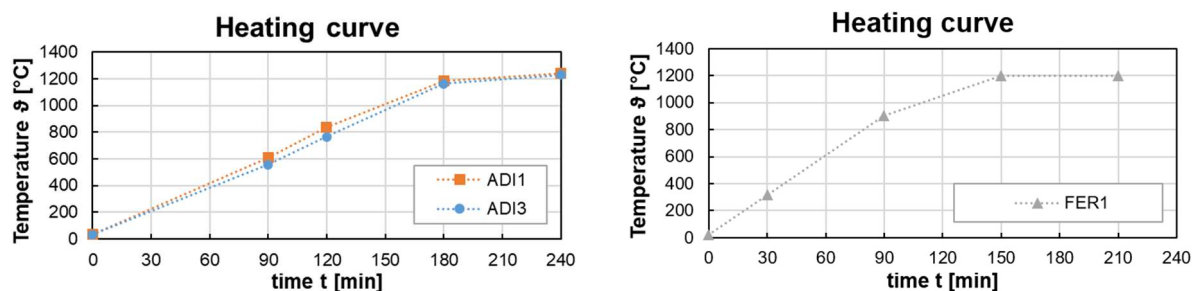


FIGURE 8: HEATING CURVES OF ADI1 AND ADI3 STEEL GRADE (LEFT) AND FER1 STEEL GRADE (RIGHT)

TABLE 2: CONSIDERED FUEL GAS COMPOSITIONS IN E-ECO DOWNSTREAM

Current and future combustion scenarios			ADI	FER
1) current combustion situation: 100 % NG or COG firing			{ADI-CG1}	{FER-CG4}
Mean fuel gas composition c_i	CH ₄	[%]	21 - 23	100
	H ₂		57 - 65	-
	CO ₂		1.04 - 1.17	-
	CO		5.11 - 5.73	-
	N ₂		6.37 - 7.67	-
	O ₂		0.85 - 1	-
Mean air number λ		[-]	0.95 - 1.2	1.1
2) possible future combustion situation: 50 % H₂ addition			{ADI-CG2}	{FER-CG5}
Mean fuel gas composition c_i	CH ₄	[%]	10.5 - 11.5	50
	H ₂		82.8 - 80.7	50
	CO ₂		0.52 - 0.59	-
	CO		2.56 - 2.87	-
	N ₂		3.19 - 3.84	-
	O ₂		0.43 - 0.50	-
Mean air number λ		[-]	0.95 - 1.2	1.1
3) possible future combustion situation: 100 % H₂ firing			{ADI-CG3}	{FER-CG6}
Mean fuel gas composition c_i	H ₂	[%]	100	100
Mean air number λ		[-]	1.1	1.1

In addition, an electrical heated holding phase in a slightly reducing gas atmosphere (N₂ + 5 % H₂) is being investigated **{SWERIM-CG7}**.

This is based on the experiments on hybrid heating of SWERIM carried out in Task 4.5. That study investigates heating via hydrogen combustion (zone 1 + 2) and through-heating in a slightly reducing atmosphere in an electrically heated soaking zone (zone 3), see **Figure 9**.

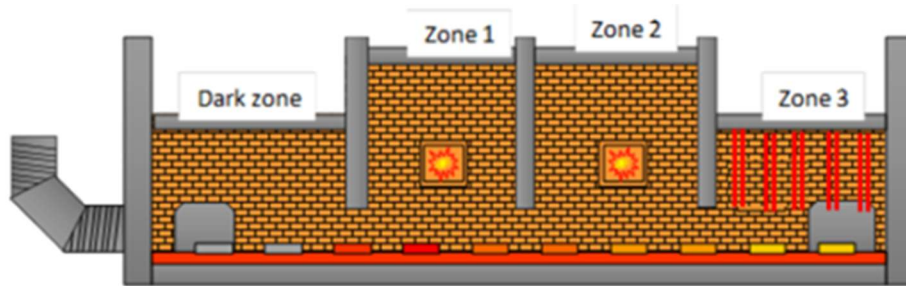


FIGURE 9: SCHEMATIC DRAWING OF THE WAKING BEAM FURNACE USED BY SWERIM IN TASK 4.5

4.3 Descaling parameters

At slab rolling mills as ADI and billed rolling mills as FER, mostly descaling systems are installed in a fixed bar or ring configuration, designed to ensure full coverage descaling on four sides respectively. **Figure 10** shows the ring-shaped spray bar (black), extended to spray vanes (blue) and a slab and a billet (red), as installed in hot rolling mills for flat and long products. Flat-jet nozzles are generally used in this kind of system.

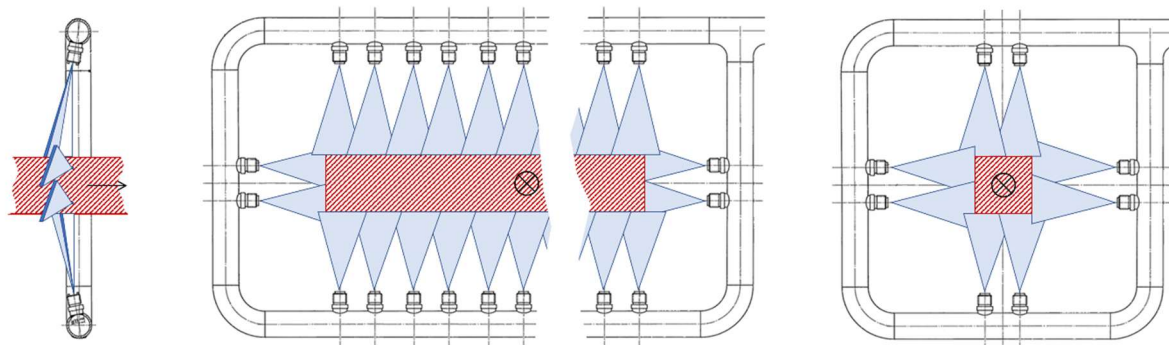


FIGURE 10: SCHEMATIC REPRESENTATION OF DESCALERS: LONGITUDINAL SECTION (LEFT), CROSS-SECTION FOR SLABS (MIDDLE) AND CROSS-SECTION FOR BILLETS (RIGHT)

The descaling parameters of the ADI production process are considered and serve as the basis for the parametrisation of the descaling tests at BFI. Using **eq. 1** to **eq. 6** results in the descaling indicators that are used at the plant as shown in **Table 3**. These values serve as the starting point for determining the parameters for the descaling tests at the BFI.

TABLE 3: DESCALING PARAMETERS AND DESCALING INDICATORS OF THE ADI PRODUCTION PROCESS

Product velocity v	[m/s]	1.0
Specific water impingement SWI	[L/m ²]	13.56
Force F	[N]	250.91
Impact pressure IP	[MPa]	0.4585
Descaling energy DE	[kJ/m ²]	4.6179

5. Test series

In E-ECO Downstream, two strategies are used to evaluate the effects of furnace operating modes on descaling.

ADI-case:

Find the set of parameters that results in approximately 20 - 80 % residual scale using the current furnace operation (combustion gas composition and heating curve) and then apply this to other combustion cases without making any other changes to the test conditions. This approach is applied to the two ADI steel grades ADI1 and ADI3 for which sample material with the original surface is available.

FER-case:

Find the set of parameters that results in approximately 20 - 80 % residual scale applying an isothermal heating in current combustion gas followed by variation of a higher number of test parameters (heating time, descaling parameter and combustion gases) to estimate a multiparametric function of the residual scale. For this test procedure a higher number of samples is needed. The tests are carried out on 1 FER steel grade, cut from billet into slices.

5.1 Test Equipment

The samples are heated up in a temperature controlled electrical heated muffle type furnace (**Figure 11, A**) connected to the gas mixing system (**Figure 11, B**) that enables the control of the combustion atmospheres as it is used for thermogravimetric analysis at BFI.



(A)



(B)

FIGURE 11: SET-UP OF THE MUFFLE TYPE FURNACE WITH POSITIONS FER1 DESCALING SAMPLES (A) AND THE GAS MIXING SYSTEM (B) AT BFI USED FOR THE DESCALING TESTS

In **Figure 12** the descaling test stand at BFI is depicted.

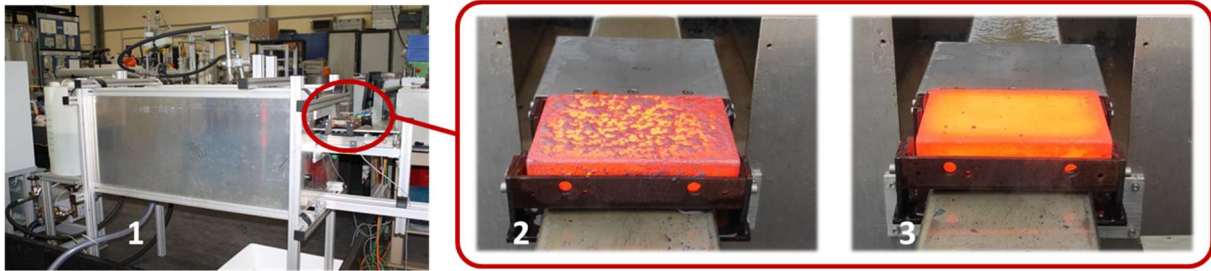


FIGURE 12: DESCALING TEST STAND (1) AS WELL AS HOT SAMPLE BEFORE (2) AND AFTER (3) DESCALING TEST

For descaling experiments after the reheating process the “MiniScalemaster” flat spray nozzle, with part number HPS 6P3.495.27 from the manufacturer Lechler, is used. It has a spray angle of $\alpha = 22^\circ$.

The performance limits of the test stand are listed in **Table 4**.

TABLE 4: PERFORMANCE LIMITS OF THE TEST STAND

Linear drive	max. 4 kg max. 3.0 m/s
Sample size	155 x 155 mm ²
Pump	Plunger pump 11 kW max. 50 L/min max. 220 bar (depending on nozzle type and number)
Descaling nozzle	Lechler HPS 6P3.495.27 17 l/min at 200 bar 22 ° spray angle

In **Figure 13** to **Figure 15** the impact pressure, the specific water impingement and the descaling energy for a:

- nozzle angle of $\beta = 5^\circ$,
- nozzle twist angle of $\gamma = 5^\circ$ and
- jet thickness angle of $\phi = 1,95^\circ$

and for variable

- spray distances h_2 ,
- pressures p and
- sample velocities v

are shown as calculated using **eq. 2** to **eq. 6**.

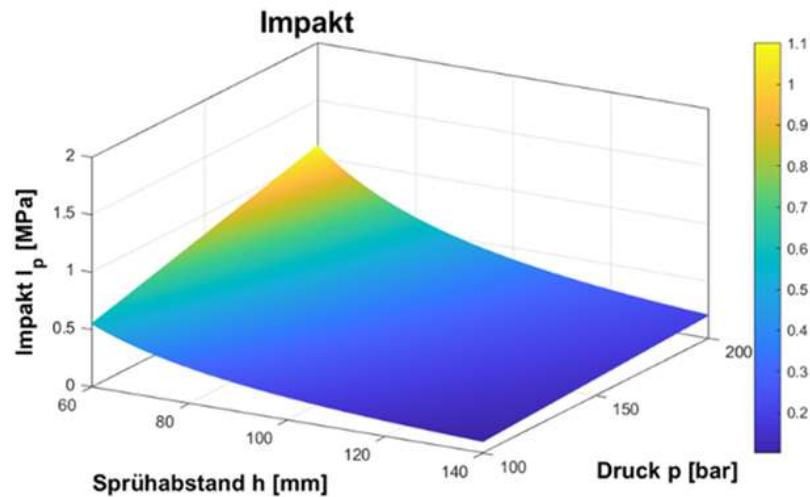


FIGURE 13: IMPACT OVER SPRAY DISTANCE AND PRESSURE

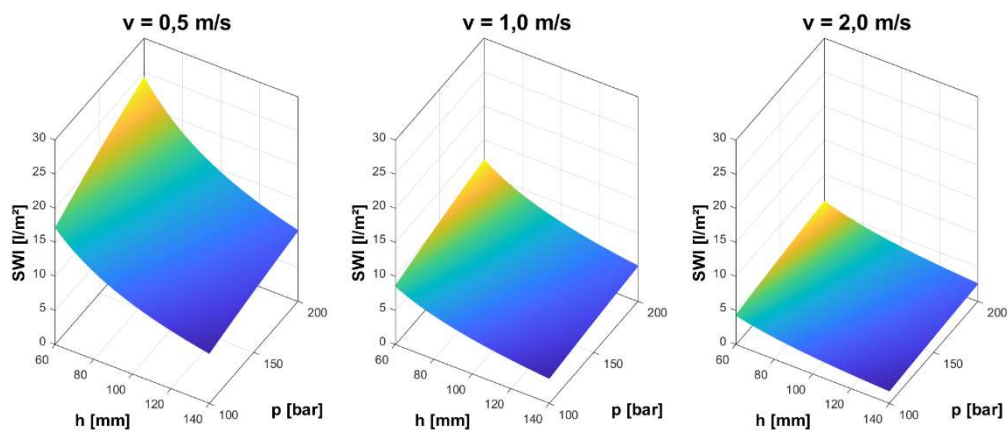


FIGURE 14: SPECIFIC WATER IMPINGEMENTS FOR DIFFERENT VELOCITIES OVER SPRAY DISTANCE AND PRESSURE

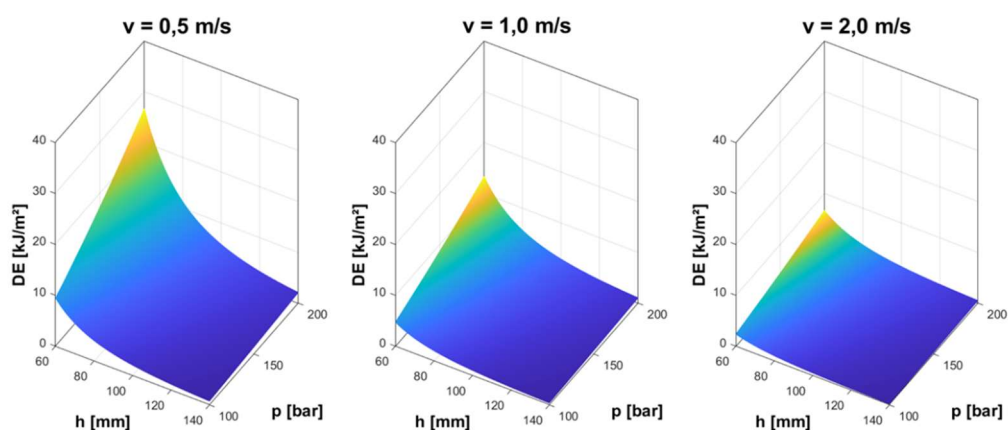


FIGURE 15: DESCALING ENERGY FOR DIFFERENT VELOCITIES OVER SPRAY DISTANCE AND PRESSURE

It becomes apparent that the test stand achieves the performance data of the industrial ADI descaling system, compare **Table 3**.

5.2 Description of the descaling test procedure at BFI

All tests on the ADI steel grades are carried out in the same way, as described in the following steps:

- 1) Heating the samples in combustion gas:
 - a. Heating up the furnace to 500 °C
 - b. Feed combustion gas to the furnace chamber
 - c. Load the furnace with a descaling sample after 5 - 10 Minutes
 - d. Heat the furnace at a rate of 5.158 K/min (from 500 to 1,200 °C within 135 minutes)
 - e. Hold the temperature for 1 hour
 - f. Remove the descaling specimen from the furnace and place in the test stand's sample holder
- 2) Programmed descaling procedure were started after 10 s after furnace removal:
 - a. photograph of the hot not-descaled sample
 - b. transport to start position
 - c. pressurise the system
 - d. transport through the high-pressure water jet
 - e. photograph of the hot descaled sample
 - f. slow air cooling of the descaled sample
- 3) Image Analysis of descaled sample to calculate the residual scale (compare **Figure 16**) using Matlab:
 - a. manual selection of the area exposed to water jet
 - b. automatic conversion of the selected area into a rectangle and crop it
 - c. separation of light and dark areas following manual selection of a grey value as a threshold
 - d. automatic calculation of the residual scale
- 4) Calculating the scale thickness depending on measured furnace temperatures (compare **Figure 16**):
 - a. Record furnace temperatures during heating of all samples
 - b. Apply the temperature files of each sample on the BFI scale growth models further developed in Task 1.5 to calculate the scale thickness

As the questions are different, the tests on FER steel grade differ slightly in point 1) as follows:

- 1) Heating the samples in combustion gas:
 - a. Heating up the furnace to 1,200 °C
 - b. Feed combustion gas to the furnace chamber
 - c. Load the furnace with a descaling sample after 5 - 10 Minutes
 - d. Hold the temperature for different times
 - e. Remove the descaling sample from the furnace and place in the test stand's sample holder

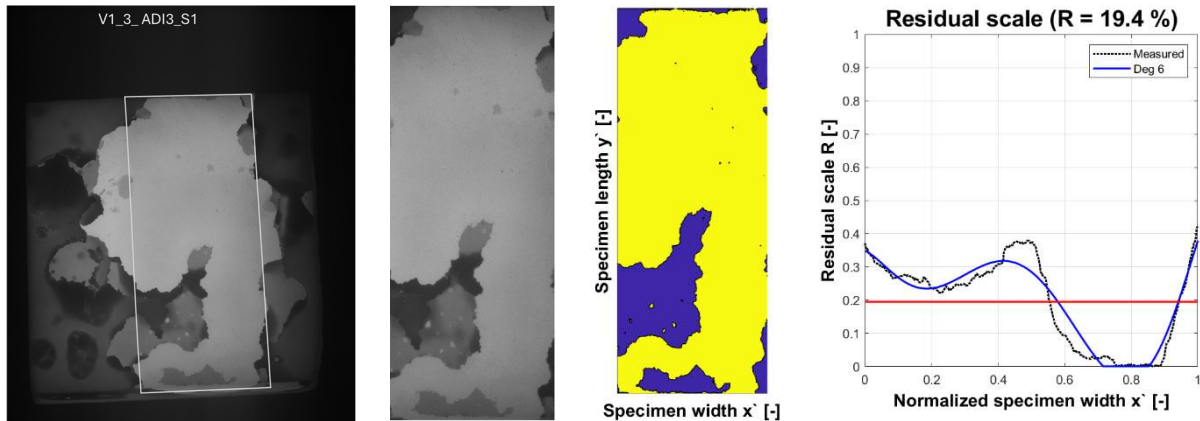


FIGURE 16: EXAMPLE PROCEDURE OF RESIDUAL SCALE CALCULATION: ORIGINAL FOTO WITH EXPOSED AREA (1), STRETCHED AND CROPPED IMAGE (2), ANALYSED GREY SCALE (3) AND CALCULATED RESIDUAL SCALE (4)

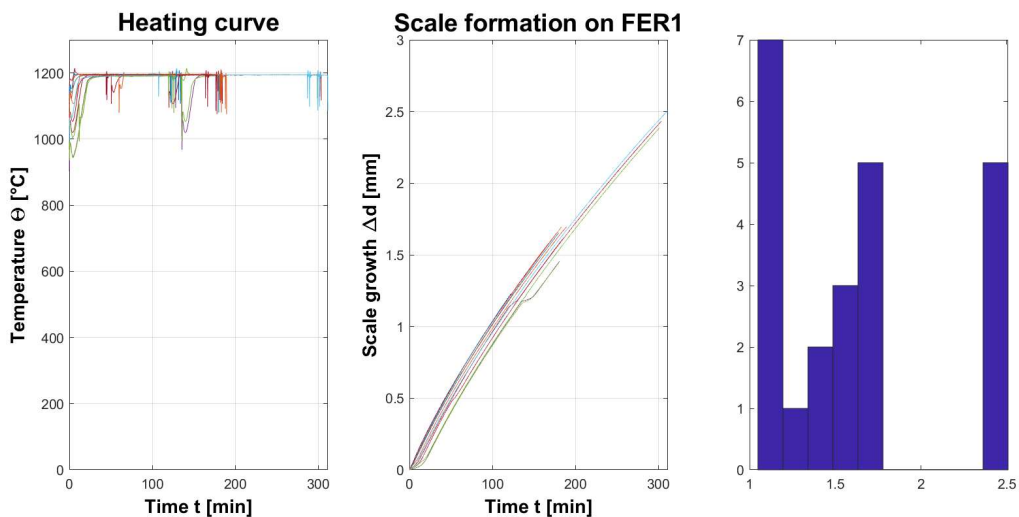


FIGURE 17: EXAMPLE OF SCALE THICKNESS CALCULATION ON FER-CG4 SAMPLE

5.3 Derivation of test parameters

For the descaling test, the descaling parameters must be selected such that approximately 20 - 80 % of the scale remains, so that the effects of variations in the individual parameters can subsequently be quantitatively described. To this end, a comparable specific water impingement and descaling energy are initially selected, with a similar impact on the sample surface to that encountered in industrial operation. The parameter combinations are adjusted from test to test until a residual scale of 20 - 80 % is achieved. This final set of parameters, called “Centre points”, forms the starting point for all further investigations per steel grade. **Figure 18 to Figure 20** show this procedure for the ADI-case from trial V0_1 to V1_3.

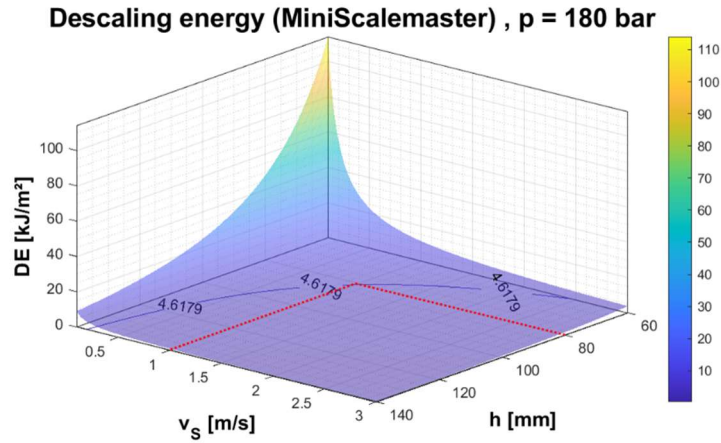


FIGURE 18: DESCALING PARAMETER SET OF THE FIRST TRIALS ON V0_1_ADI1_P1 AND V0_1_ADI3_S3

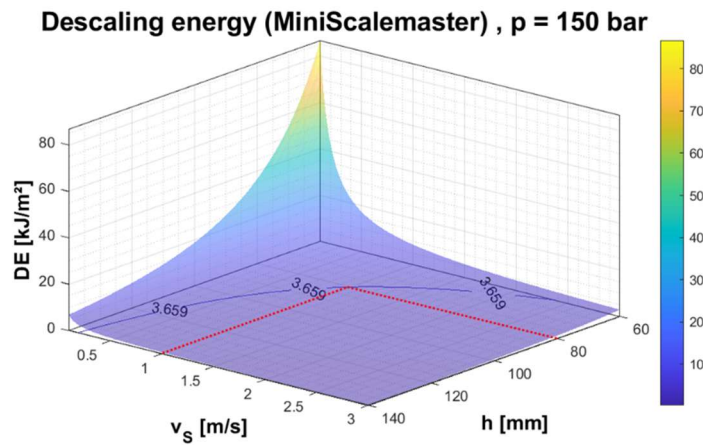


FIGURE 19: DESCALING PARAMETER SET OF THE SECOND TRIALS ON V0_2_ADI1_P4 AND V0_2_ADI3_S9

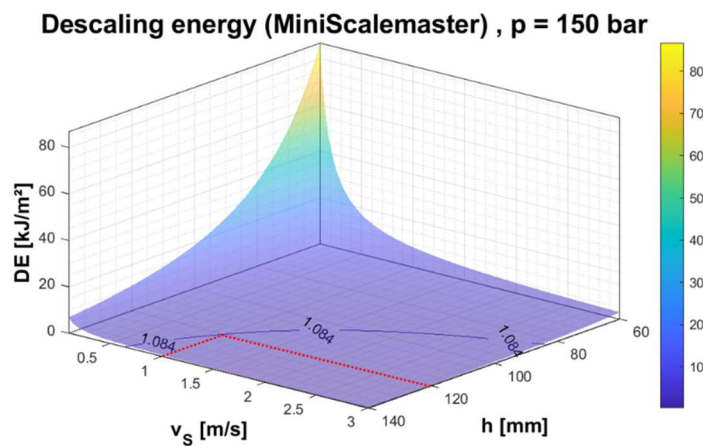


FIGURE 20: DESCALING PARAMETER SET OF THE THIRD TRIALS V1_3_ADI1_P2 AND V1_3_ADI3_S1

The final test parameters (that leads not to fully or completely not descaled surface) in this way are listed in **Table 5**. For the ADI-case, only the combustion gases are

changed, whilst the Centre points remain the same. For the FER-case, a wider parameter range around the Centre points is defined using the Design of Experiments method to find a multiparametric function of residual scale R depending on the most influencing process parameters. This range is defined by the “Corner points”.

TABLE 5: FINAL DESCALING TEST PARAMETER RANGE: CENTRE AND CORNER POINTS

		ADI	FER
Product velocity v	[m/s]	1.0	0.5, 0.75, 1.0
Vertical spray height h_2	[mm]	120	100, 120, 140
Water pressure p	[bar]	150	130, 150, 185
Heating time t	[min]	195 ^{*1}	120, 180, 300
Angel of Inclination β	[°]	5	5
Offset angel of the nozzle γ	[-]	5	5
No. of nozzles	[-]	1	1
<i>*1: including heating up</i>			

The simulated combustion gases are shown in **Table 6**.

TABLE 6: FURNACE ATMOSPHERES FOR ADI AND FER SAMPLES

Current and future combustion scenarios				ADI	FER
1) current combustion situation: 100 % NG or COG firing				{ADI-CG1}	{FER-CG4}
Combustion gas composition c_i	N ₂	[%]	70.2	72.1	
	O ₂		3.0	1.7	
	CO ₂		5.5	8.7	
	H ₂ O		21.3	17.5	
2) possible future combustion situation: 50 % H ₂ addition				{ADI-CG2}	{FER-CG5}
Combustion gas composition c_i	N ₂	[%]	69.0	70.8	
	O ₂		3.0	1.7	
	CO ₂		3.3	6.9	
	H ₂ O		24.7	20.6	
3) possible future combustion situation: 100 % H ₂ firing				{ADI-CG3}	{FER-CG6}
Combustion gas composition c_i	N ₂	[%]	66.3	66.3	
	O ₂		1.6	1.6	
	CO ₂		0.0	0.0	
	H ₂ O		32.1	32.1	
4) possible future combustion situation: 100 % H ₂ firing and subsequent electrical heating in slightly reducing atmosphere				{SWERIM-CG7}	
Combustion gas composition c_i	N ₂	[%]	66.3		
	O ₂		1.6		
	CO ₂		0.0		
	H ₂ O		32.1		

6. Results

In **Table 7** and **Table 8** all test parameters and results are listed.

TABLE 7: DESCALING TEST PARAMETERS AND RESULTS FOR ADI-CASE

Steel grade	Trial	ADI sample	Combustion scenario	Water content CH ₂ O [%]	Oxygen content CO ₂ [%]	Vertical distance h ₂ [mm]	Pressure p [bar]	Heating time t [min]	Spec. water impingement SWI	Impact pressure IP [MPa]	Descaling energy DE	Scale thickness d [mm]	Residual scale R [%]
ADI1	V0_1_ADI1	P1	ADI-CG1	21.2	3.1	80	180	183	8.63	0.56	4.810	1.040	1.3
	V0_2_ADI1	P4	ADI-CG1	21.2	3.1	80	150	191	7.88	0.46	3.659	1.088	12.2
	V1_3_ADI1	P2	ADI-CG1	21.2	3.1	120	150	193	5.25	0.21	1.084	1.127	8.0* ³
	V1_4_ADI1	P3	ADI-CG2	24.6	3.0	120	150	193	5.25	0.21	1.084	1.222	10.5
	V1_5_ADI1	P5	ADI-CG3	34.7	0.0* ¹	120	150	0	5.25	0.21	1.084		11.8
	V1_7_ADI1	P6	ADI-CG3	32.0	1.6	120	150	195	5.25	0.21	1.084	0.961	0.5
	V1_8_ADI1	P1* ²	ADI-CG3	32.0	1.6	120	150	196	5.25	0.21	1.084	0.971	98.8
	V1_9_ADI1	P4* ²	SWERIM-CG7	32.0	1.6	120	150	197	5.25	0.21	1.084	0.434	73.5
ADI3	V0_1_ADI3	S3	ADI-CG1	21.2	3.1	80	180	184	8.63	0.56	4.810	1.023	2.6
	V0_2_ADI3	S9	ADI-CG1	21.2	3.1	80	150	192	7.88	0.46	3.659	1.070	2.8
	V1_3_ADI3	S1	ADI-CG1	21.2	3.1	120	150	193	5.25	0.21	1.084	1.119	19.4
	V1_4_ADI3	S2	ADI-CG2	24.6	3.0	120	150	194	5.25	0.21	1.084	1.230	44.9
	V1_5_ADI3	S5	ADI-CG3	34.7	0.0* ¹	120	150	0	5.25	0.21	1.084		63.0
	V1_7_ADI3	S8	ADI-CG3	32.0	1.6	120	150	196	5.25	0.21	1.084	1.036	1.0
	V1_8_ADI3	S3* ²	ADI-CG3	32.0	1.6	120	150	198	5.25	0.21	1.084	1.054	40.9
	V1_9_ADI3	S9* ²	SWERIM-CG7	32.0	1.6	120	150	198	5.25	0.21	1.084	0.395	12.4
*1: Contrary to the plan, 0 % O₂ was set in the furnace atmosphere. It was not possible to calculate the scale layer thickness. *2: The samples were used twice. It was not possible to carry out a cross-sectional analysis. *3: Scale was detached but not washed away from the surface. The measured residual scale amounts were corrected manually.													

TABLE 8: DESCALING TEST PARAMETERS AND RESULTS FOR FER-CASE

Trial	Combustion scenario	Water content CH ₂ O [%]	Oxygen content CO ₂ [%]	Vertical distance h ₂ [mm]	Pressure p [bar]	Speed v [m/s]	Heating time t [min]	Spec. water impingement SWI	Impact pressure IP [MPa]	Descaling energy DE	Scale thickness d [mm]	Residual scale R [%]
V0_1_FER1_1	FER-CG4	17.5	1.7	120	180	1.00	121	5.75	0.25	1.425	1.127	1.9
V0_1_FER1_2	FER-CG4	17.5	1.7	120	150	1.00	123	5.25	0.21	1.084	1.144	0.6
V0_1_FER1_3	FER-CG4	17.5	1.7	160	150	1.00	128	3.94	0.12	0.457	1.181	99.7
V0_1_FER1_4	FER-CG4	17.5	1.7	120	150	1.00	181	5.25	0.21	1.084	1.551	96.9
V0_1_FER1_5	FER-CG4	17.5	1.7	120	150	0.50	179	10.50	0.21	2.168	1.630	1.7
V1_1_FER1_6	FER-CG4	17.5	1.7	120	150	0.75	183	7.00	0.21	1.446	1.655	5.0 ^{*1}
V1_1_FER1_7	FER-CG4	17.5	1.7	120	165	0.75	185	7.34	0.23	1.668	1.671	1.8
V1_1_FER1_8	FER-CG4	17.5	1.7	120	185	1.00	180	5.83	0.25	1.485	1.693	15.0
V1_2_FER1_1	FER-CG4	17.5	1.7	140	185	1.00	122	5.00	0.19	0.935	1.123	65.9
V1_2_FER1_2	FER-CG4	17.5	1.7	140	130	1.00	124	4.19	0.13	0.551	1.136	21.3
V1_2_FER1_3	FER-CG4	17.5	1.7	120	130	1.00	126	4.89	0.18	0.875	1.155	91.0
V1_2_FER1_4	FER-CG4	17.5	1.7	140	130	1.00	180	4.19	0.13	0.551	1.548	98.6
V1_2_FER1_5	FER-CG4	17.5	1.7	100	130	1.00	302	5.87	0.26	1.512	2.499	99.2
V1_2_FER1_6	FER-CG4	17.5	1.7	100	185	1.00	304	7.00	0.37	2.566	2.509	91.4
V1_2_FER1_7	FER-CG4	17.5	1.7	120	150	0.75	188	7.00	0.21	1.446	1.737	0.6
V1_2_FER1_8	FER-CG4	17.5	1.7	120	150	0.75	190	7.00	0.21	1.446	1.747	1.3
V1_3_FER1_1	FER-CG4	17.5	1.7	120	130	0.75	119	6.52	0.18	1.166	1.118	48.7
V1_3_FER1_2	FER-CG4	17.5	1.7	100	130	0.75	298	7.82	0.26	2.015	2.454	3.2
V1_3_FER1_3	FER-CG4	17.5	1.7	120	185	0.75	301	7.78	0.25	1.980	2.471	0.5 ^{*1}
V1_3_FER1_4	FER-CG4	17.5	1.7	140	185	0.50	299	10.00	0.19	1.870	2.579	0.5 ^{*1}

Trial	Combustion scenario	Water content C _{H2O} [%]	Oxygen content C _{O2} [%]	Vertical distance h ₂ [mm]	Pressure p [bar]	Speed v [m/s]	Heating time t [min]	Spec. water impingement SWI	Impact pressure IP [MPa]	Descaling energy DE	Scale thickness d [mm]	Residual scale R [%]
V1_3_FER1_5	FER-CG4	17.5	1.7	140	185	0.50	178	10.00	0.19	1.870	1.687	5.0 ^{*1}
V1_3_FER1_6	FER-CG4	17.5	1.7	140	130	0.50	122	8.38	0.13	1.102	1.247	7.3
V1_3_FER1_7	FER-CG4	17.5	1.7	140	130	0.50	183	8.38	0.13	1.102	1.726	1.6
V1_4_FER1_1	FER-CG5	20.6	1.7	110	140	0.60	155	4.50	0.15	0.683	1.220	0.6
V1_4_FER1_2	FER-CG5	20.6	1.7	110	175	0.60	247	9.22	0.23	2.115	1.785	86.9
V1_5_FER1_1	FER-CG6	31.9	1.7	130	140	0.90	152	5.20	0.16	0.854	2.190	0.3
V1_5_FER1_2	FER-CG6	31.9	1.7	110	175	0.60	242	10.31	0.29	2.956	1.521	8.0
V1_6_FER1_1	FER-CG6	31.9	1.7	120	150	1.00	117	5.25	0.21	1.084	1.049	99.3
V1_6_FER1_2	FER-CG6	31.9	1.7	120	130	1.00	119	5.83	0.25	1.485	1.062	8.0
V1_6_FER1_3	FER-CG6	31.9	1.7	100	185	1.00	299	7.00	0.37	2.566	2.421	100.0
V1_6_FER1_4	FER-CG6	31.9	1.7	100	150	1.00	302	7.63	0.44	3.328	2.432	95.9
*1: Scale was detached but not washed away from the surface. The measured residual scale amounts were corrected manually.												

6.1 Discussion

6.1.1 ADI-case

A sensitivity analyses (a map of correlation coefficients according to Bravais-Pearson) of each influencing factor pairs are carried. The results are a statistical number that measures the strength and direction of a linear relationship between two variables. The closer the value is to $|1|$, the stronger the correlation is. That analyses show that both ADI steel grades react differently with residual scale to the process parameters.

- ADI1 is mostly affected by descaling parameters that have an influence on the descaling energy, compare **Figure 22**.
- ADI3 is additionally affected by the combustion atmosphere, compare **Figure 22**.

	Legend									
	-1.0	-0.7	-0.3	0.0	0.3	0.7	1.0	X=Y		
ADI1	H ₂ O content c _{H2O} [%]	O ₂ content c _{O2} [%]	Vertical distance h [mm]	Pressure p [bar]	Spec. water impingement SWI [L/m ²]	Impact IP [MPa]	Force F [N]	Descaling energy DE [kJ/m ²]	Scale Thickness d [mm]	Residual scale R [%]
H ₂ O content c _{H2O} [%]	1.0	-0.9	0.6	-0.4	-0.6	-0.6	-0.4	-0.6	-0.6	0.2
O ₂ content c _{O2} [%]	-0.9	1.0	-0.5	0.3	0.5	0.5	0.3	0.5	0.6	-0.1
Vertical distance h [mm]	0.6	-0.5	1.0	-0.7	-1.0	-1.0	-0.7	-1.0	-0.4	0.4
Pressure p [bar]	-0.4	0.3	-0.7	1.0	0.8	0.8	1.0	0.8	0.2	-0.3
Spec. water impingement SWI [L/m ²]	-0.6	0.5	-1.0	0.8	1.0	1.0	0.8	1.0	0.4	-0.5
Impact IP [MPa]	-0.6	0.5	-1.0	0.8	1.0	1.0	0.8	1.0	0.4	-0.5
Force F [N]	-0.4	0.3	-0.7	1.0	0.8	0.8	1.0	0.8	0.2	-0.3
Descaling energy DE [kJ/m ²]	-0.6	0.5	-1.0	0.8	1.0	1.0	0.8	1.0	0.4	-0.5
Scale Thickness d [mm]	-0.6	0.6	-0.4	0.2	0.4	0.4	0.2	0.4	1.0	-0.3
Residual scale R [%]	0.2	-0.1	0.4	-0.3	-0.5	-0.5	-0.3	-0.5	-0.3	1.0

FIGURE 21: SENSITIVITY ANALYSES OF THE DESCALING INFLUENCING FACTORS FOR ADI1

Legend												-1.0	-0.7	-0.3	0.0	0.3	0.7	1.0	X ≡ Y
ADI3	H ₂ O content c _{H2O} [%]	1.0	-0.9	0.6	-0.4	-0.6	-0.6	-0.4	-0.6	-0.5	0.5								
	O ₂ content c _{O2} [%]	-0.9	1.0	-0.5	0.3	0.5	0.5	0.3	0.5	0.5	-0.6								
	Vertical distance h [mm]	0.6	-0.5	1.0	-0.7	-1.0	-1.0	-0.7	-1.0	-0.3	0.5								
	Pressure p [bar]	-0.4	0.3	-0.7	1.0	0.8	0.8	1.0	0.8	0.1	-0.3								
	Spec. water impingement SWI [L/m ²]	-0.6	0.5	-1.0	0.8	1.0	1.0	0.8	1.0	0.3	-0.5								
	Impact IP [MPa]	-0.6	0.5	-1.0	0.8	1.0	1.0	0.8	1.0	0.3	-0.5								
	Force F [N]	-0.4	0.3	-0.7	1.0	0.8	0.8	1.0	0.8	0.1	-0.3								
	Descaling energy DE [kJ/m ²]	-0.6	0.5	-1.0	0.8	1.0	1.0	0.8	1.0	0.3	-0.5								
	Scale Thickness d [mm]	-0.5	0.5	-0.3	0.1	0.3	0.3	0.1	0.3	1.0	0.1								
	Residual scale R [%]	0.5	-0.6	0.5	-0.3	-0.5	-0.5	-0.3	-0.5	0.1	1.0								

FIGURE 22: SENSITIVITY ANALYSES OF THE DESCALING INFLUENCING FACTORS FOR ADI3

Based on these findings, the individual results of the descaling tests are depicted in **Figure 23** and **Figure 24** to show the influence of a higher water vapor and oxygen content as well as the descaling energy on the residual scale.

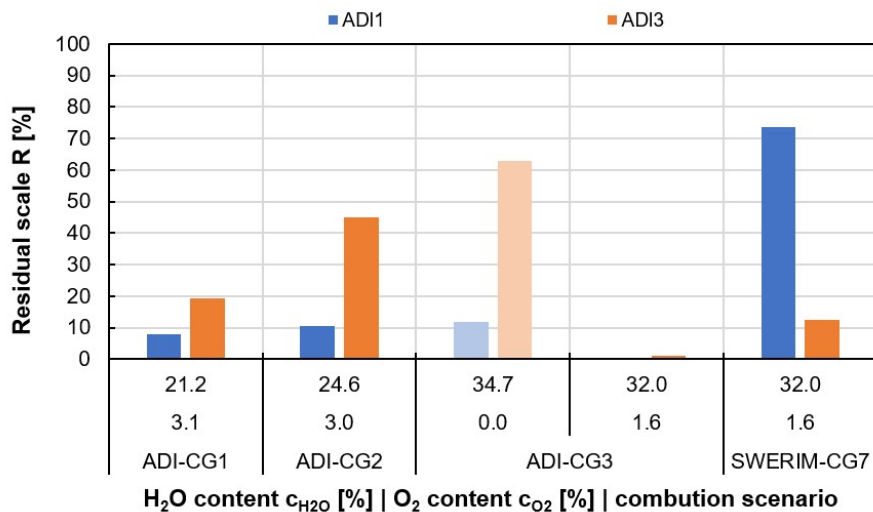


FIGURE 23: INFLUENCE OF A HIGHER WATER VAPOR CONTENT ON THE RESIDUAL SCALE ON ADI1 AND ADI3

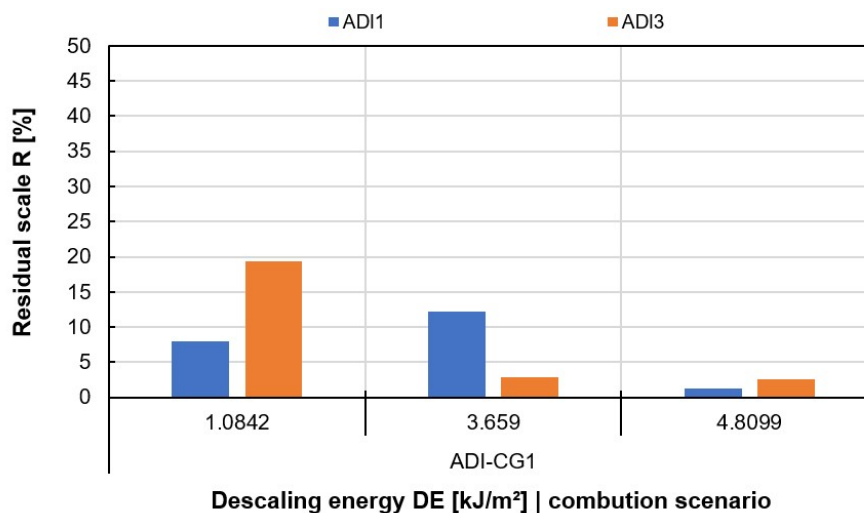


FIGURE 24: INFLUENCE OF THE DESCALING ENERGY ON THE RESIDUAL SCALE ON ADI1 AND ADI3

It is noticeable that:

- ADI1 steel grade descaling is still well, almost independently of the water vapour content (compare ADI-CG1, ADI-CG2 and ADI-CG3), but tends to retain residual scale when through-heated in an inert atmosphere (compare SWERIM-CG7).
- ADI3 steel grade descaling becomes more difficult as the water vapour content in the combustion gas increases and the oxygen content decreases (compare ADI-CG1, ADI-CG2 and ADI-CG3); however, inert heating can lead to better descaling results (compare SWERIM-CG7).

The results showing very low residual scale amount in ADI-CG3 with 1.6 % O₂ in the combustion gas cannot be explained.

Figure 25 shows two examples of descaled samples from ADI1 and ADI3. This example clearly demonstrates that both steel grades form scale with different fracture patterns:

- The scale on ADI1 shows low adhesion but high cohesion. It has what is known as a 'weak interface'. This can be recognised by the fact that the descaled area is, over a large area, completely free of adhering sub-layers. This behaviour is observed in steels with relatively low amounts of alloying elements.
- The scale on ADI3 shows low cohesion but high adhesion. It has what is known as a 'strong interface'. This can be recognised by the presence of several layers of residual scale in the area exposed to water. This behaviour is observed in steels with higher amounts of alloying elements, particularly manganese, silicon and microalloying elements.

Taking into account the mechanisms of descaling described at the beginning and the assumption that water vapour makes the scale more ductile and tough, it also becomes apparent that ADI3 is descaled depending on the water vapour content, because, in addition to the high adhesion, the cohesion is also increased. Conversely, it becomes

apparent that ADI1 is descaled almost independently of the water vapour content, as cohesion is not a decisive factor from the outset.

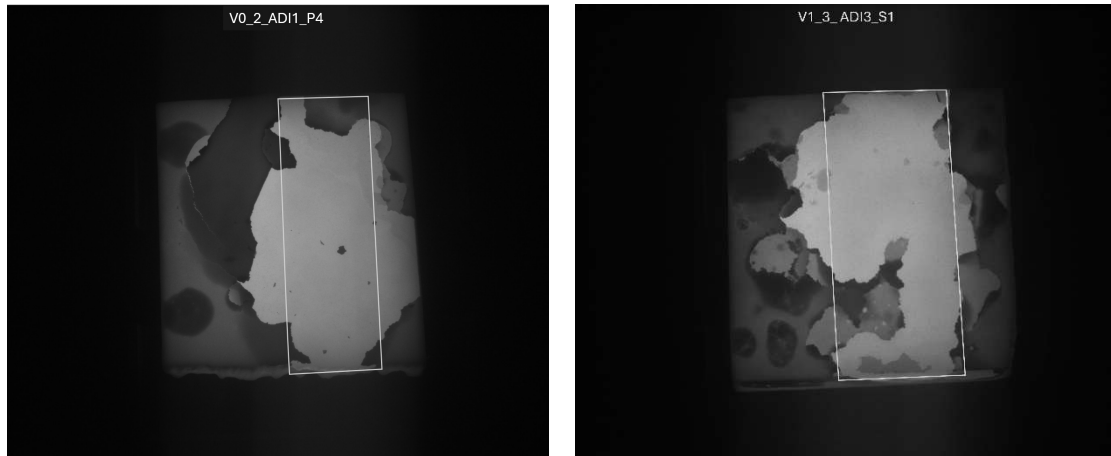


FIGURE 25: INFLUENCE OF THE DESCALING ENERGY ON THE RESIDUAL SCALE ON ADI1 AND ADI3

6.1.2 FER-case

The data from all experiments were used in a regression analysis to derive a multiparametric function of the residual scale R [%] as a function of several variable parameters of the type given in **eq. 7**.

$$\text{eq. 7} \quad Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_{ii}^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k \beta_{ij} X_i X_j$$

As a first step, the following influencing factors were defined for scenario FER-CG4 (pure NG combustion):

- spray distance h [mm]
- pressure p [bar]
- velocity v [m/s]
- scale layer thickness d [mm]

The result of the multi-parameter function containing only linear terms, is given by **eq. 8** with a relative residuum of 57 %.

$$\text{eq. 8} \quad R = 0.6169 * h - 0.5063 * p + 148.529 * v + 25.451 * d - 128.9$$

It becomes clear that, as expected, the residual scale R increases when:

- spray distance h increases,
- pressure p decreases,
- velocity v increases and
- scale layer thickness d increases.

The result of the multi-parameter function containing linear, quadratic and interaction terms, in which the influencing factors that result in the lowest normalised coefficients are eliminated is given by **eq. 9** with a relative residuum of 56 %.

$$\begin{aligned} \text{eq. 9} \quad R = & 7.7109 * h - 7.1551 * p + 0.6851 * v + 0.8007 * d - 0.0339 * h^2 + 1.6117 * v^2 \\ & + 1.9176 * d^2 + 1.0219 * dp - 1.1282 * dh - 0.9199 * vh + 1.7341 \\ & * vp + 3.5087 * vd + 0.0278 * ph + 0.32 \end{aligned}$$

This function is plotted graphically as a 4D contour plot and depicted **Figure 26**.

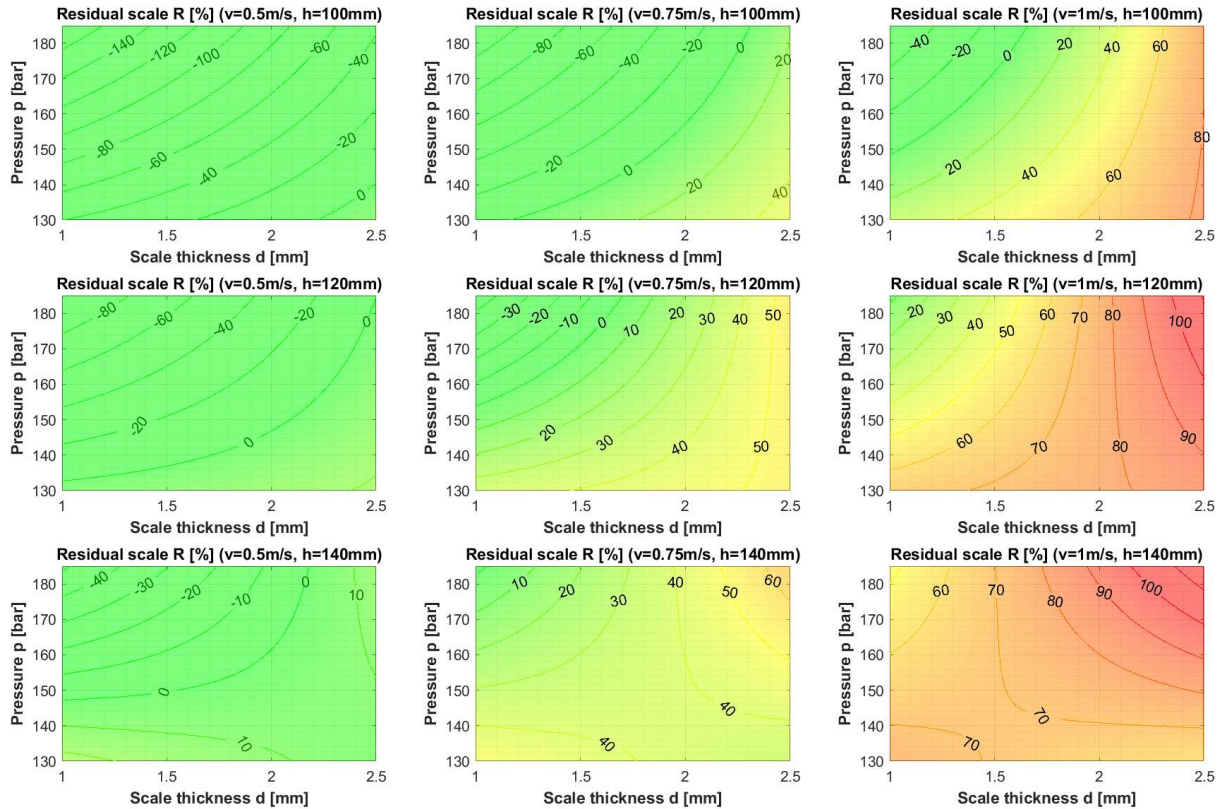


FIGURE 26: 4D CONTOUR PLOT OF R DEPENDING ON D, P, V AND H

The residual scale is illustrated as follows using false-colour mapping:

- Green: $R \leq 0 \%$
- Yellow: $R = 50 \%$
- Red: $R \geq 100 \%$

It becomes apparent that the at higher spray distance h and velocity v the residual scale the residual scale behaves differently than expected.

In a second step, instead of descaling parameters the descaling indicators are chosen for scenarios FER-CG4, FER-CG5 and FER-CG6 (combustion of natural gas with hydrogen addition) to describe in addition the influence of the H2 addition to the NG on the descaling. The influencing factors are defined as:

- Impact pressure IP [MPa]
- Specific water impingement SWI [L/m^2]
- Hydrogen addition to natural gas $H2$ [%]
- Scale thickness d [mm]

The result of the multi-parameter function containing only linear terms, is given by **eq. 10** with a relative residuum of 64%.

eq. 10
$$R = 197.2683 * IP - 10.973 * SWI + 0.218 * H2 + 5.9655 * d + 54.4346$$

It can therefore be concluded that, the residual scale R increases when:

- impact pressure IP increases,
- specific water impingement SWI decreases,
- hydrogen addition to natural gas $H2$ increases and
- scale layer thickness d increases.

The negative effect of the impact pressure on the descaling result is not estimated.

The result of the multi-parameter function containing linear, quadratic and interaction terms, in which the influencing factors that result in the lowest normalised coefficients are eliminated is given by **eq. 11** with a relative residuum of 56 %.

eq. 11
$$\begin{aligned} R = & 7.7109 * h - 7.1551 * p + 0.6851 * v + 0.8007 * d - 0.0339 * h^2 + 1.6117 * v^2 \\ & + 1.9176 * d^2 + 1.0219 * dp - 1.1282 * dh - 0.9199 * vh + 1.7341 \\ & * vp + 3.5087 * vd + 0.0278 * ph + 0.32 \end{aligned}$$

This function is plotted graphically as a 4D contour plot and depicted **Figure 26**.

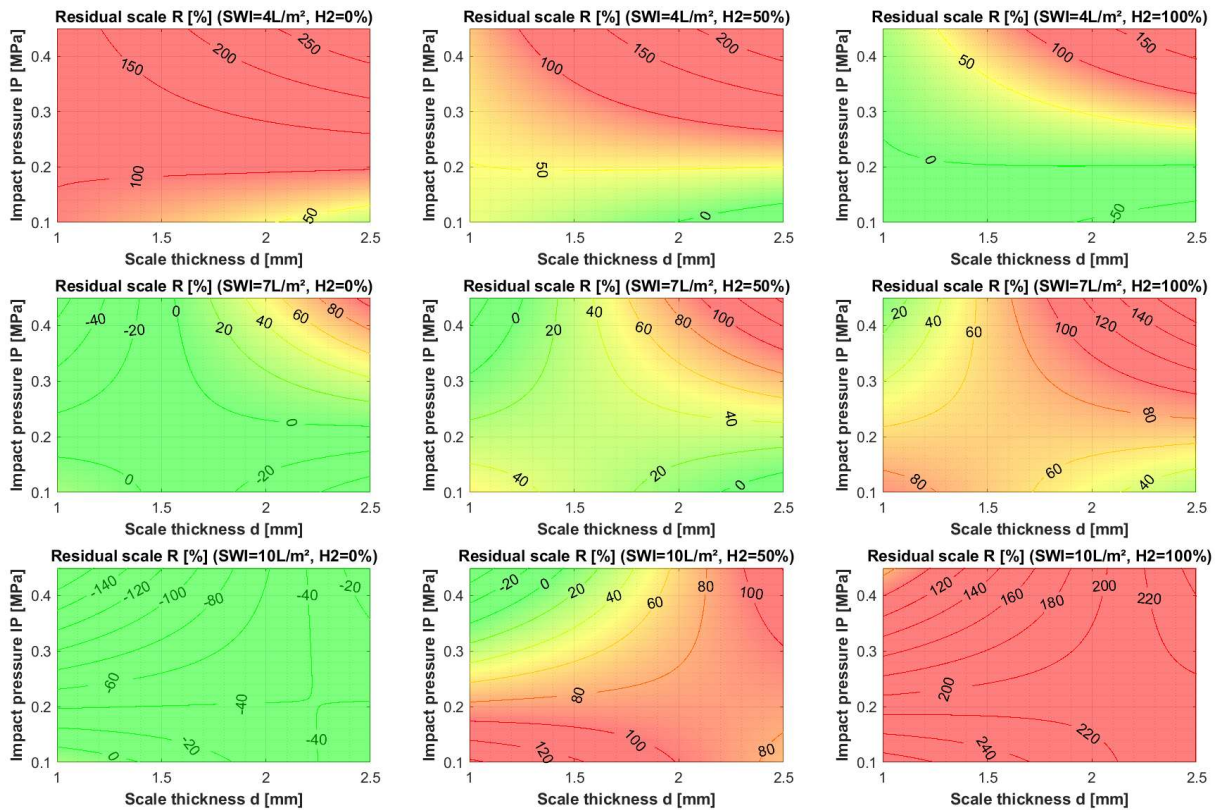


FIGURE 27: 4D CONTOUR PLOT OF R DEPENDING ON D, IP, SWI AND H2

The attempt to identify a plausible, suitable multi-parameter function has failed in this case. This may be because the experimental results are cut off below 0 % and above 100 %, which, in the case of linear regression, leads to increased inaccuracies at the edges of the parameter space. The application of a Generalized Linear Model could lead to better results in the future.

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List of acronyms and abbreviations

Acronym	Full Name
COG	Coke oven gas
H2	hydrogen
NG	natural gas