

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Fuel cell technologies –

**Part 8-301: Energy storage systems using fuel cell modules in reverse mode –
Power-to-methane energy systems based on solid oxide cells including
reversible operation – Performance test methods**

Technologies des piles à combustible –

**Partie 8-301: Systèmes de stockage de l'énergie utilisant des modules à piles à
combustible en mode inversé – Systèmes de conversion de l'énergie en
méthane à base de piles à oxyde solide, comprenant le fonctionnement
réversible – Méthodes d'essai des performances**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

FUEL CELL TECHNOLOGIES –

Part 8-301: Energy storage systems using fuel cell modules in reverse mode – Power-to-methane energy systems based on solid oxide cells including reversible operation – Performance test methods

FOREWORD

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IEC 62282-8-301 has been prepared by IEC technical committee 105: Fuel cell technologies. It is an International Standard.

The text of this International Standard is based on the following documents:

Draft	Report on voting
105/968/FDIS	105/983/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 62282 series, published under the general title *Fuel cell technologies*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

This part of IEC 62282 describes performance evaluation methods for electric energy conversion systems based on power-to-methane systems using solid oxide cells (SOCs) and methanation reactors.

A typical application of the power-to-methane systems is an electrolytic production of methane as the energy carrier suitable for a large-scale, long-term storage and transportation.

The combustion heat of methane per mol is about three times larger than that of hydrogen. Methane is easily liquefied, which makes it suitable for storage and transportation via existing infrastructures for natural gas (tanks, pipelines, tankers, or trucks) as well as for being easily utilized by conventional equipment. Also, the use of "green methane" (produced by renewable electricity) or "carbon neutral methane" in place of "fossil methane" is a promising option in the near future.

The IEC 62282-8 series aims to develop performance test methods for power storage and buffering systems based on electrochemical modules (combining electrolysis and fuel cells, in particular reversible cells), taking into consideration both options of re-electrification and substance (and heat) production for the sustainable integration of renewable energy sources.

Under the general title "Energy storage systems using fuel cell modules in reverse mode", the IEC 62282-8 series consists of the following parts:

- IEC 62282-8-101: Test procedures for the performance of solid oxide single cells and stacks, including reversible operation
- IEC 62282-8-102: Test procedures for the performance of single cells and stacks with proton exchange membrane, including reversible operation
- IEC 62282-8-103¹: Alkaline single cell and stack performance including reversible operation
- IEC 62282-8-201²: Test procedures for the performance of power-to-power systems
- IEC 62282-8-202³: Power-to-power systems – Safety
- IEC 62282-8-3xy (all parts): Power-to-substance systems

As a priority dictated by the emerging needs for industry and the opportunities for technological development, IEC 62282-8-101, IEC 62282-8-102 and IEC 62282-8-201 were initiated jointly.

This document is the first of the IEC 62282-8-3xy series.

¹ Under consideration.

² Second edition under preparation. Stage at the time of publication: IEC CDV 62282-8-201:2023.

³ Under consideration.

FUEL CELL TECHNOLOGIES –

Part 8-301: Energy storage systems using fuel cell modules in reverse mode – Power-to-methane energy systems based on solid oxide cells including reversible operation – Performance test methods

1 Scope

This part of IEC 62282 specifies performance test methods of power-to-methane systems based on solid oxide cells (SOCs). Water, CO₂, and electricity are supplied to the system to produce methane and oxygen.

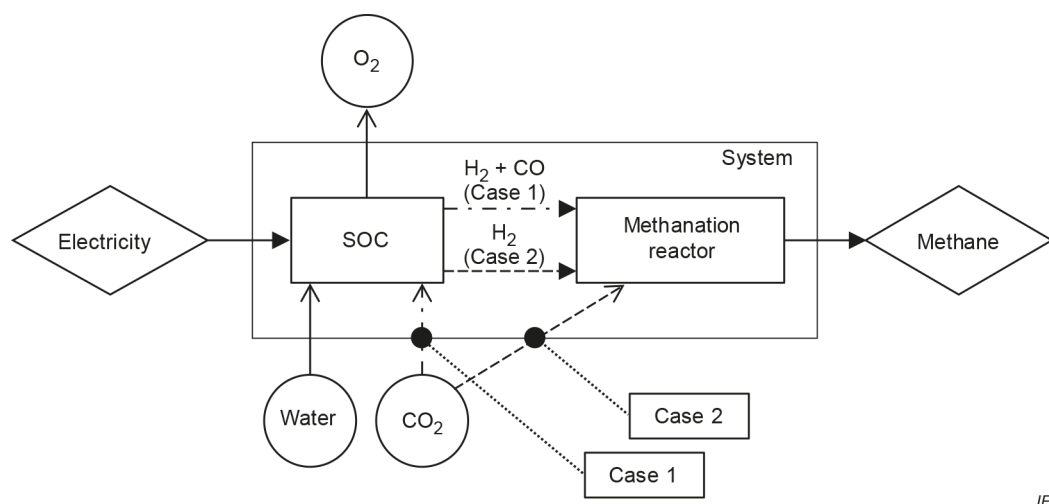
This document is not intended to be applied to solid oxide fuel cell (SOFC) cell/stack assembly units for power generation purposes only, since these are covered in IEC 62282-7-2. In addition, the test methods for SOC cell/stack assembly units including reversible operation (without any methanation reactor) are already described in IEC 62282-8-101. Users can substitute the selected test methods of this document with the equivalent test methods given in IEC 62282-8-101 (solid oxide electrolysis cell (SOEC) to produce H₂ only as well as SOFC operation mode and reversible mode) and in IEC 62282-7-2 (SOFC mode only).

This document covers two types of processes as shown in Figure 1:

- Case 1: Steam and CO₂ are introduced into the SOC (co-electrolysis process), and the product gas (mainly, H₂ + CO) is supplied to a methanation reactor (catalytic reactor);
- Case 2: Steam is introduced into the SOC to generate H₂, which is supplied into a methanation reactor with CO₂.

Besides these two cases, the methanation catalyst can be integrated within the SOC, but this case is not within the scope of this document. This document provides, for testing systems, information on instruments and specifies measurement methods to test the performance of SOC cell/stack assembly units and of the methanation reactor for energy conversion purposes. To produce CH₄ from water and CO₂, the SOC is operated in electrolysis mode (solid oxide electrolysis cell (SOEC)). The SOC can be operated either in fuel cell mode (SOFC) or in reversible operation mode or both. In this document, the system is considered not to have components which store electricity, fluids, or heat.

This document is intended to be used for data exchanges in commercial transactions between the system manufacturers and customers. Users of this document can selectively execute test items suitable for their purposes from those described in this document.



IEC

Figure 1 – Process schematic of the scope of IEC 62282-8-301

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60584-1, *Thermocouples – Part 1: EMF specifications and tolerances*

IEC 60584-3, *Thermocouples – Part 3: Extension and compensating cables – Tolerances and identification system*

IEC 61515, *Mineral insulated metal-sheathed thermocouple cables and thermocouples*

IEC 62282-7-2:2021, *Fuel cell technologies – Part 7-2: Test methods – Single cell and stack performance tests for solid oxide fuel cells (SOFC)*

IEC 62282-8-101:2020, *Fuel cell technologies – Part 8-101: Energy storage systems using fuel cell modules in reverse mode – Test procedures for the performance of solid oxide single cells and stacks, including reversible operation*

ISO 5167-1, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – Part 1: General principles and requirements*

ISO 5168, *Measurement of fluid flow – Procedures for the evaluation of uncertainties*

ISO 6141, *Gas analysis – Contents of certificates for calibration gas mixtures*

ISO 6142-1, *Gas analysis – Preparation of calibration gas mixtures – Part 1: Gravimetric method for Class I mixtures*

ISO 6143, *Gas analysis – Comparison methods for determining and checking the composition of calibration gas mixtures*

ISO 6145-7, *Gas analysis – Preparation of calibration gas mixtures using dynamic methods – Part 7: Thermal mass-flow controllers*

ISO 6974 (all parts), *Natural gas – Determination of composition and associated uncertainty by gas chromatography*

ISO 6975, *Natural gas – Extended analysis – Gas-chromatographic method*

ISO 7066-2, *Assessment of uncertainty in the calibration and use of flow measurement devices – Part 2: Non-linear calibration relationships*

ISO 8573-1, *Compressed air – Part 1: Contaminants and purity classes*

ISO 8756, *Air quality – Handling of temperature, pressure and humidity data*

ISO 10101 (all parts), *Natural gas – Determination of water by the Karl Fischer method*

ISO 11541, *Natural gas – Determination of water content at high pressure*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1.1

active electrode area

effective electrode area

geometric area of the electrode where the electrochemical reaction takes place

Note 1 to entry: Usually this corresponds to the smaller of the two areas of negative electrode or positive electrode.

Note 2 to entry: Area perpendicular to the ionic current flow, usually expressed in m^2 or cm^2 .

[SOURCE: IEC 62282-8-101:2020, 3.1.1]

3.1.2

additional gas

gas added to the product gas from the negative electrode for the reaction in the methanation reactor

Note 1 to entry: For Case 2 in Figure 1, the additional gas is CO_2 .

Note 2 to entry: For Case 1 in Figure 1 (co-electrolysis mode), CO_2 or H_2 or both can be added to convert the product gas from the negative electrode into CH_4 efficiently.

3.1.3

area-specific resistance

ASR

internal resistivity of any component of a cell or a stack, including the change of potential due to the electrochemical reaction

Note 1 to entry: It is normalized by the active electrode area and is expressed in $\Omega \cdot \text{m}^2$ or $\Omega \cdot \text{cm}^2$.

[SOURCE: IEC 62282-8-101:2020, 3.1.2]

3.1.4**catalyst**

substance that accelerates a reaction without being consumed itself

[SOURCE: IEC 60050-485:2020, 485-01-01, modified – "electrochemical reaction" has been replaced by "reaction" and Note 1 and Note 2 have been deleted.]

3.1.5**cell**

single cell

basic unit of a solid oxide cell

[SOURCE: IEC 62282-8-101:2020, 3.1.7, modified – "cell" has become a preferred term.]

3.1.6**cold state**

state of a power-to-methane system at ambient temperature with no power input or output

Note 1 to entry: The cold state can come after the storage state during cooling-down of the system.

[SOURCE: IEC 60050-485:2020, 485-21-01, modified – "fuel cell power system" has been replaced by "power-to-methane system" and the Note to entry has been added.]

3.1.7**compression force**

axial load

compressive load applied to the single cell or to the end plates of a planar SOC stack to ensure electric contact and gas tightness

Note 1 to entry: The compression force is in practice expressed in N.

[SOURCE: IEC 62282-8-101:2020, 3.1.7, modified – The preferred term "axial load" has become an admitted term and the admitted term "compression force" has become a preferred term.]

3.1.8**conditioning**

preliminary step of treatment that is required to properly operate a SOC and is usually realized by following a protocol specified by the manufacturer

[SOURCE: IEC 62282-8-101:2020, 3.1.8, modified – The Note 1 to entry has been deleted.]

3.1.9**conversion of CO₂ into CH₄**

catalytic conversion percentage of carbon dioxide into methane in the methanation reactor

3.1.10**conversion of H₂ into CH₄**

catalytic conversion percentage of hydrogen into methane in the methanation reactor

3.1.11**current density**

electric current per unit active area of the electrode

Note 1 to entry: The current density is expressed in A/m² or A/cm².

[SOURCE: IEC 60050-485:2020, 485-12-01, modified – "of the electrode" has been added and the domain has been deleted.]

3.1.12

electrode gas

gas present at the positive or negative electrode

Note 1 to entry: Electrode gases can be reactants, products or inert gas.

[SOURCE: IEC 62282-8-101:2020, 3.1.14]

3.1.13

interconnector

interconnect

electronically conductive and gas-tight component connecting single cells in a stack

[SOURCE: IEC 62282-8-101:2020, 3.1.4, modified – "electronically" has been added and the Notes to entry have been deleted.]

3.1.14

methanation reactor

catalytic reactor which converts CO_2 , CO , and H_2 into CH_4

3.1.15

negative electrode

electrode at which fuel (reductant) gas is consumed or produced

Note 1 to entry: In the case of electrolysis mode with an oxide-ion conducting electrolyte such as yttria-stabilized zirconia in a SOC, steam is reduced to produce hydrogen or a mixture of steam and CO_2 is reduced to produce H_2 + CO .

Note 2 to entry: In the case of electrolysis mode for a proton conducting SOC, the negative electrode gas is hydrogen or inert gas or both (Case 2 in Figure 1) or a mixture of hydrogen, CO_2 and inert gas (Case 1, co-electrolysis).

[SOURCE: IEC 62282-8-101:2020, 3.1.19, modified – "(reductant)" has been added and the three Notes to entry have been replaced with two new Notes to entry.]

3.1.16

positive electrode

electrode at which oxygen is consumed or produced

Note 1 to entry: In the case of electrolysis mode for an oxide-ion conducting SOC, the positive electrode gas is usually air to carry the generated oxygen.

Note 2 to entry: In the case of electrolysis mode for a proton conducting SOC, the positive electrode gas is steam or a mixture of steam and inert gas to carry the generated oxygen.

[SOURCE: IEC 62282-8-101:2020, 3.1.21, modified – The three Notes to entry have been replaced with two new Notes to entry.]

3.1.17

protection gas

mixture of hydrogen and inert gas (usually argon or nitrogen) to protect the transition metal-containing negative electrodes of the SOC and the catalyst in the methanation reactor from being re-oxidized in case of abnormal operating conditions (e.g. electrode gas interruption, emergency stop of the test station)

3.1.18

rated conditions

recommended operation conditions (e.g. current, power) as specified by the manufacturer, at which the SOC system has been designed to operate

3.1.19**reversible mode**

regenerative mode

operation mode of a solid oxide cell which alternates between fuel cell mode and electrolysis mode (Re-SOC)

Note 1 to entry: The term "reversible" in this context does not refer to the thermodynamic principle of an ideal process.

[SOURCE: IEC 62282-8-101:2020, 3.1.26]

3.1.20**shutdown time**

time required for shutdown from the rated state to the cold state

Note 1 to entry: The shutdown time is expressed in s, min, or h.

3.1.21**shutdown energy**

total energy input during shutdown from the rated state to the cold state

Note 1 to entry: The shutdown energy is expressed in kJ.

3.1.22**solid oxide cell**

SOC

electrochemical cell composed of three functional elements (negative electrode, electrolyte and positive electrode)

[SOURCE: IEC 62282-8-101:2020, 3.1.28, modified – "based on ceramic oxide materials" and the three Notes to entry have been deleted.]

3.1.23**solid oxide electrolysis cell**

SOEC

SOC operated in electrolysis mode

[SOURCE: IEC 62282-8-101:2020, 3.1.29, modified – "i.e. reversed fuel cell mode" and the three Notes to entry have been deleted.]

3.1.24**solid oxide fuel cell**

SOFC

SOC operated in fuel cell mode

[SOURCE: IEC 62282-8-101:2020, 3.1.30, modified – Note 1 to entry has been deleted.]

3.1.25**space velocity**

quotient of the entering volumetric flow rate of the reactants divided by the volume of the catalyst bed

Note 1 to entry: The space velocity is expressed in 1/s.

3.1.26**stable state**

condition of a cell/stack assembly unit at which the unit is stable enough for any controlling parameter and the output voltage or output current of the unit to remain within its tolerance range of variation

[SOURCE: IEC 62282-7-2:2021, 3.1.9]

3.1.27**stack**

assembly of cells, interconnectors, cooling plates, manifolds and a supporting structure

[SOURCE: IEC 60050-485:2020, 485-06-01, modified – The first preferred term "fuel cell stack" has been deleted, "separators" has been replaced by "interconnectors" and "that electrochemically converts, typically, hydrogen-rich gas and air reactants to DC power, heat and other reaction products" has been deleted.]

3.1.28**start-up time**

time required for start-up from the cold state to the rated state

Note 1 to entry: The start-up time is expressed in s, min, or h.

3.1.29**start-up energy**

total energy input during start-up from the cold state to the rated state

Note 1 to entry: The start-up energy is expressed in kJ.

3.1.30**storage state**

state of a power-to-methane system being non-operational and possibly requiring, under conditions specified by the manufacturer, the input of thermal and electric energy, or an inert atmosphere, or any combination thereof, in order to prevent deterioration of the components and to energize the control systems

[SOURCE: IEC 60050-485-21-06, modified – "fuel cell power system" has been replaced by "power-to-methane system" and "to energize the control systems" has been added.]

3.1.31**sweep gas**

gas supplied to the positive electrode compartment of the SOC to carry the generated oxygen

Note 1 to entry: Air is frequently used as the sweep gas in the case of an oxide-ion conduction SOC to carry generated O₂ gas. For a proton-conducting SOC, steam or a mixture of steam and inert gas is supplied to carry the generated O₂.

3.1.32**test input parameter**

TIP

parameter whose values can be set in order to define the test conditions of the test system including the operating conditions of the test object

[SOURCE: IEC 62282-8-101:2020, 3.1.33, modified – The Note 1 to entry has been deleted.]

3.1.33**test output parameter**

TOP

parameter that indicates the response of the test system/test object as a result of variation of TIPs

[SOURCE: IEC 62282-8-101:2020, 3.1.34, modified – The Note 1 to entry has been deleted.]

3.2 Abbreviated terms and symbols**3.2.1 Abbreviated terms**

AC	alternating current
ASR	area-specific resistance
CE	current efficiency
DC	direct current
DR	degradation rate
FT	Fischer Tropsch
GWP	global warming potential
HHV	higher heating value
LHV	lower heating value
P2G	power-to-gas
SOC	solid oxide cell
SOEC	solid oxide electrolysis cell
SOFC	solid oxide fuel cell
Re-SOC	reversible solid oxide cell
STP	standard temperature and pressure
SV	space velocity
TIP	test input parameter
TOP	test output parameter

3.2.2 Symbols

Table 1 lists the symbols and units that are used in this document.

Table 1 – Symbols

Symbol	Definition	Unit(s)
A_{active}	Active (geometric) area of the cell/stack electrode(s)	m ² , cm ²
c	Concentration	
c_i	Molar concentration of component i	mol/m ³
C_p	Heat capacity	
$C_{p,c}$	Heat capacity of the heat transfer fluid at standard pressure	J/(kg · K)
$C_{p,i}$	Heat capacity of component i at standard pressure	J/(kg · K)
E	Energy	
$E_{\text{el,in}}$	Electric energy input to the system	kJ
$E_{\text{el,out}}$	Electric energy output from the system	kJ
$E_{\text{sp,CH}_4}$	Specific electric energy consumed for producing a unit volume of CH ₄	kJ/m ³

Symbol	Definition	Unit(s)
E_{st}	Start-up energy of the system	kJ
E_{sd}	Shutdown energy of the system	kJ
F	Faraday constant, force	
F	Faraday constant (96 485,3)	C/mol
F_{comp}	Compression force applied onto the cell/stack	N
f	Frequency	
f	Excitation frequency for impedance measurement	Hz
H	Higher heating value	
H_{CH_4}	Higher heating value of methane	kJ/mol
I, J	Current, current density	
I_{AC}	Alternating current (AC current) supplied to the system	A
I_{cell}	Cell current	A
I_{DC}	DC current supplied to the system	A
I_{stack}	Stack current	A
I_{pk}	Amplitude of alternating current	A
J	Current density	A/m ² , A/cm ²
δJ	Differential change in current density	A/m ² , A/cm ²
N, n	Number of items	
N_{cell}	Number of cells in the assembly unit	
n	Number of carbon atoms in a hydrocarbon molecule	
P	Power	
P_{AC}	AC electric power supplied to the system	W
P_{DC}	DC electric power supplied to the system	W
$P_{th,MR}$	Heat (thermal power) recovery rate at the methanation reactor	kJ/s
$P_{th,sys,in}$	Sum of heat (thermal power) input rate of all heat transferring fluids of the system	kJ/s
$P_{th,sys,out}$	Sum of heat (thermal power) output rate of all heat transferring fluids of the system	kJ/s
$\Delta P_{th,sys}$	Heat (thermal power) balance of the system	kJ/s
p	Pressure	
$p_{neg,in}$	Pressure of negative electrode gas at cell/stack inlet	kPa
$p_{neg,out}$	Pressure of negative electrode gas at cell/stack outlet	kPa
$p_{pos,in}$	Pressure of positive electrode gas at cell/stack inlet	kPa
$p_{pos,out}$	Pressure of positive electrode gas at cell/stack outlet	kPa
p_{ad}	Pressure of the additional gas	kPa
$p_{MR,in}$	Pressure of gas at methanation reactor inlet	kPa
$p_{MR,out}$	Pressure of gas at methanation reactor outlet	kPa
p_0	Standard pressure (101,325)	kPa
V	Volume	
V_{cat}	volume of the catalyst bed	m ³

Symbol	Definition	Unit(s)
Q_{th}	Heat (thermal) energy	
$Q_{th,in}$	Heat (thermal) energy input to the system	kJ
$Q_{th,out}$	Heat (thermal) energy output from the system	kJ
q_m	Mass flow rate	
$q_{m,c}$	Mass flow rate of heat recovery fluid	kg/s
q_V	Volumetric flow rate	
$q_{V,H}$	Volumetric flow rate of heat transfer fluid (at STP)	m ³ /s
$q_{V,neg,in}$	Total volumetric flow rate at negative electrode inlet (at STP)	m ³ /s
$q_{V,pos,in}$	Total volumetric flow rate at positive electrode inlet (at STP)	m ³ /s
$q_{V,neg,out}$	Total volumetric flow rate at negative electrode outlet (at STP)	m ³ /s
$q_{V,pos,out}$	Total volumetric flow rate at positive electrode outlet (at STP)	m ³ /s
$q_{V,ad}$	Total volumetric flow rate of the additional gas (at STP)	m ³ /s
$q_{V,MR,in}$	Total volumetric flow rate at methanation reactor inlet (at STP)	m ³ /s
$q_{V,MR,out}$	Total volumetric flow rate at methanation reactor outlet (at STP)	m ³ /s
$q_{V,i,neg,in}$	Volumetric flow rate of gas component i at negative electrode inlet (at STP)	m ³ /s
$q_{V,i,pos,in}$	Volumetric flow rate of gas component i at positive electrode inlet (at STP)	m ³ /s
$q_{V,i,neg,out}$	Volumetric flow rate of gas component i at negative electrode outlet (at STP)	m ³ /s
$q_{V,i,pos,out}$	Volumetric flow rate of gas component i at positive electrode outlet (at STP)	m ³ /s
$q_{V,i,ad}$	Volumetric flow rate of gas component i in the additional gas (at STP)	m ³ /s
$q_{V,i,MR,in}$	Volumetric flow rate of gas component i at methanation reactor inlet (at STP)	m ³ /s
$q_{V,i,MR,out}$	Volumetric flow rate of gas component i at methanation reactor outlet (at STP)	m ³ /s
$q_{V,product,sys,out}$	Total volumetric flow rate of product gas at the outlet of the system (at STP)	m ³ /s
$q_{V,i,sys,out}$	Volumetric flow rate of gas component i at the outlet of the system (at STP)	m ³ /s
$q_{V,i,sys,in}$	Volumetric flow rate of gas component i at the inlet of the system (at STP)	m ³ /s
R	Resistance, universal gas constant	
R	Resistance	Ω
R_{ASR}	Area-specific resistance	Ω · m ² , Ω · cm ²
R_{ohm}	Ohmic resistance	Ω
$R_{non-ohm}$	Non-ohmic resistance	Ω
R_g	Universal gas constant (8,314 5)	J/(mol · K)
r	Production rate of gas	
r_i	Production rate of gas component i at electrode outlet (at STP)	m ³ /s
$r_{H_2,neg,out}$	Production rate of hydrogen gas at negative electrode outlet (at STP)	m ³ /s
$r_{H_2,eq,neg,out}$	Production rate of gas equivalent to hydrogen at negative electrode outlet (at STP)	m ³ /s

Symbol	Definition	Unit(s)
SV	Space velocity	
SV	quotient of the entering volumetric flow rate of reactants divided by the volume of the catalyst bed	1/s
T	Temperature	
$T_{c,in}$	Temperature of the heat recovery fluid at the inlet of the methanation reactor	K
$T_{c,out}$	Temperature of the heat recovery fluid at the outlet of the methanation reactor	K
$T_{cell/stack}$	Temperature of the cell or stack	K
$T_{stack,av}$	Average temperature of the stack	K
$T_{stack,intern}$	Internal stack temperature	K
T_{BP}	Temperature of the bottom plate	K
T_{TP}	Temperature of the top plate	K
$T_{furnace}$	Temperature of the furnace	K
$T_{neg,in}$	Temperature of negative electrode gas stream at cell/stack inlet	K
$T_{pos,in}$	Temperature of positive electrode gas stream at cell/stack inlet	K
$T_{neg,out}$	Temperature of negative electrode gas stream at cell/stack outlet	K
$T_{pos,out}$	Temperature of positive electrode gas stream at cell/stack outlet	K
$T_{PH,neg}$	Temperature of the pre-heater for preheating the negative electrode gas stream	K
$T_{PH,pos}$	Temperature of the pre-heater for preheating the positive electrode gas stream	K
T_{ad}	Temperature of the additional gas stream	K
$T_{H,in}$	Temperature of heat transfer fluid input	K
$T_{H,out}$	Temperature of heat transfer fluid output	K
$T_{PH,ad}$	Temperature of the pre-heater for preheating the additional gas stream	K
$T_{MR,in}$	Temperature of gas stream at methanation reactor inlet	K
$T_{MR,out}$	Temperature of gas stream at methanation reactor outlet	K
$T_{PH,MR}$	Temperature of the pre-heater for preheating the methanation reactor gas stream	K
T_0	Standard temperature (273,15)	K
t	Time	s, min, h
t_{acq}	Data acquisition time	s, min, h
t_{dur}	Measurement duration	s, min, h
t_{eq}	Equilibration time	s, min, h
t_{op}	Duration time of operation at given conditions	s, min, h
t_0	Initial time	-
t_1	End time	-
t_{MR}	Residence time for the methanation reactor	s
V	Voltage	
V_{AC}	AC voltage supplied to the system	V
V_{cell}	Voltage of the cell	V

Symbol	Definition	Unit(s)
$V_{\text{cell,av}}$	Average cell voltage	V
V_{DC}	DC voltage supplied to the system	V
V_{stack}	Voltage of the stack	V
V_{pk}	Amplitude of alternating voltage	V
V_{th}	Thermodynamic voltage based on HHV or LHV	V
x	Fraction	
x_i	Molar fraction of component i	mol/mol
$x_{i,\text{neg,in}}$	Molar fraction of component i in the negative electrode gas stream inlet at cell/stack	mol/mol
$x_{i,\text{neg,out}}$	Molar fraction of component i in the negative electrode gas stream outlet at cell/stack	mol/mol
$x_{i,\text{pos,in}}$	Molar fraction of component i in the positive electrode gas stream inlet at cell/stack	mol/mol
$x_{i,\text{pos,out}}$	Molar fraction of component i in the positive electrode gas stream outlet at cell/stack	mol/mol
$x_{i,\text{ad}}$	Molar fraction of component i in the additional gas stream	mol/mol
$x_{i,\text{MR,in}}$	Molar fraction of component i in the gas stream at methanation reactor inlet	mol/mol
$x_{i,\text{MR,out}}$	Molar fraction of component i in the gas stream at methanation reactor outlet	mol/mol
$x_{i,\text{sys,in}}$	Molar fraction of component i in the product gas at system inlet	mol/mol
$x_{i,\text{sys,out}}$	Molar fraction of component i in the product gas at system outlet	mol/mol
$x_{m,i}$	Mass fraction of component i	kg/kg
$x_{\text{H}_2\text{O}}$	Steam molar fraction	mol/mol
x_{H_2}	Hydrogen molar fraction	mol/mol
x_{CO_2}	CO ₂ molar fraction	mol/mol
x_{CO}	CO molar fraction	mol/mol
x_{O_2}	Oxygen molar fraction	mol/mol
y	Conversion	
$y_{\text{CH}_4/\text{H}_2}$	Conversion of H ₂ into CH ₄	%
$y_{\text{CH}_4/\text{CO}_2}$	Conversion of CO ₂ into CH ₄	%
Y, Z	Impedance	
Z	Impedance	Ω
	Specific impedance	$\Omega \cdot \text{cm}^2, \Omega \cdot \text{m}^2$
$ Z $	Modulus of impedance	Ω
	Modulus of specific impedance	$\Omega \cdot \text{cm}^2, \Omega \cdot \text{m}^2$
Z'	Real part of impedance (resistance)	Ω
	Real part of specific impedance	$\Omega \cdot \text{cm}^2, \Omega \cdot \text{m}^2$
Z''	Imaginary part of impedance (reactance)	Ω
	Imaginary part of specific impedance	$\Omega \cdot \text{cm}^2, \Omega \cdot \text{m}^2$
η	Efficiency	
η_{CE}	Current efficiency	%
η_{CH_4}	CH ₄ production efficiency	%

Symbol	Definition	Unit(s)
η_{el}	Electrolytic efficiency	%
η_{total}	Total efficiency of the system	%
η_V	Voltage efficiency	%
λ	Power factor	
λ	Power factor	-
ρ	Density	
ρ_H	Density of heat transfer fluid	kg/m ³

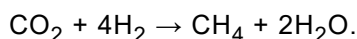
4 Power-to-methane system based on SOC

The use of electricity generated from renewable energy sources such as solar and wind power has been increasing worldwide. However, such a renewable electricity is intermittent in nature. To match the electricity supply with demand, an efficient and cost-effective storage technology is required. An electrolytic production of gases (power-to-gas, such as hydrogen, methane, or syngas) as the energy carrier is suitable for large-scale, long-term storage and transportation. Fuel cell modules can be operated in reverse mode to act as the electrolyser. Specifically, solid oxide cells (SOCs), operating at high temperature, produce such gases efficiently in solid oxide electrolysis cell (SOEC) mode and generate electricity in solid oxide fuel cell (SOFC) mode with the identical cell components.

Among gases produced, the combustion heat per mole of methane is about three times larger than that of hydrogen. Methane is easily liquefied, which makes it suitable for storage and transportation via existing infrastructures for natural gas (tanks, pipelines, tankers, or trucks) as well as providing an easy utilization by conventional equipment. Also, the use of "green methane" or "carbon neutral methane" in place of "fossil methane" is a promising option for the near future.

Since methane has a higher global warming potential (GWP) than CO₂, ensuring that there is no fugitive emissions of both the CO₂ reactant and the CH₄ product during the testing is important.

It is possible, in principle, to produce methane by supplying CO₂ and hydrogen to a catalytic methanation reactor:



Because the methanation reaction is exothermic (252,96 kJ/mol, higher heating value), a combination of the SOC and the methanation reactor can very efficiently utilize the heat generated by the methanation reaction in the endothermic operation of the SOEC. One possibility is the co-electrolysis of CO₂ and H₂O in the SOEC with the product gas (H₂, CO, CH₄, etc.) being supplied to the methanation reactor, displayed for Case 1 of Figure 1. Another possibility is steam electrolysis in the SOEC to produce H₂, followed by the methanation reaction with supplying CO₂ (Case 2 in Figure 1). In the former case (co-electrolysis), the product gas including H₂ and CO can also be supplied to an alternative catalytic reactor to produce methanol, dimethylether, gasoline, or other chemicals, besides the methanation reactor.

This document addresses procedures providing performance test methods of the power-to-methane system using SOCs, but it can also be applied to power-to-liquid (or power-to-X) systems.

5 Reference conditions

5.1 Temperature and pressure

In this document, gas volumes and volumetric flow rates at the standard temperature and standard pressure (STP) are used, following common practice. The standard temperature is 273,15 K, and the standard pressure is 101,325 kPa. Gas volume and volumetric flow rate can be replaced, in principle, by mass of gas and mass flow rate, taking into consideration the molar mass and density of the species considered.

5.2 Heating value base

The following heating values at 25 °C are used:

- lower heating value of hydrogen (formation heat of water vapour): $\text{LHV}_{\text{H}_2} = 241,82 \text{ kJ/mol}$;
- higher heating value of hydrogen (formation heat of liquid water): $\text{HHV}_{\text{H}_2} = 285,83 \text{ kJ/mol}$;
- lower heating value of methane: $\text{LHV}_{\text{CH}_4} = 802,55 \text{ kJ/mol}$;
- higher heating value of methane: $\text{HHV}_{\text{CH}_4} = 890,58 \text{ kJ/mol}$;

NOTE 1 These heating values are cited from ISO 6976:2016.

- higher heating value of the methanation reaction: $\text{HHV}_{\text{methanation}} = 252,74 \text{ kJ/mol}$;

NOTE 2 This value is calculated based on HHV_{H_2} and HHV_{CH_4} shown above: $4 \times \text{HHV}_{\text{H}_2} - \text{HHV}_{\text{CH}_4}$.

- higher heating value for the overall co-electrolysis reaction, $\text{CO}_2 + 3\text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 + 2\text{O}_2$: $\text{HHV}_{\text{co-electrolysis}} = -1\,140,47 \text{ kJ/mol}$;

NOTE 3 This value is calculated based on HHV_{H_2} shown above and the heating value of CO, $\text{HV}_{\text{CO}} = 282,98 \text{ kJ/mol}$ cited from ISO 6976:2016: $-3 \times \text{HHV}_{\text{H}_2} - \text{HV}_{\text{CO}}$.

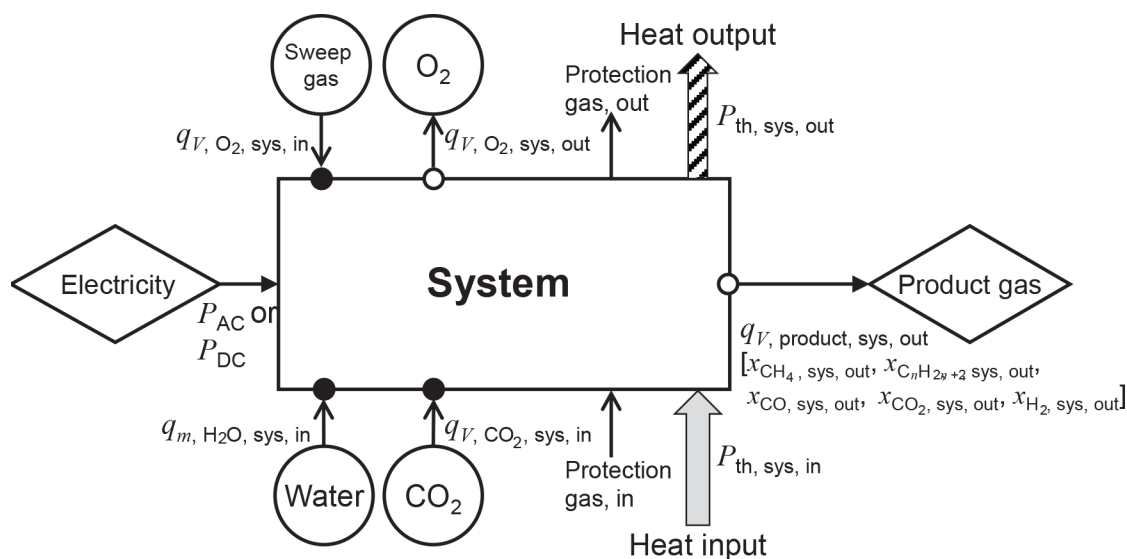
- lower heating value for the overall co-electrolysis reaction: $\text{LHV}_{\text{co-electrolysis}} = -1\,008,44 \text{ kJ/mol}$.

NOTE 4 This value is calculated based on LHV_{H_2} shown above and the heating value of CO, $\text{HV}_{\text{CO}} = 282,98 \text{ kJ/mol}$ cited from ISO 6976:2016: $-3 \times \text{LHV}_{\text{H}_2} - \text{HV}_{\text{CO}}$.

6 Instrumentation and measurement methods

6.1 General

Figure 2 shows the physical interfaces of the system (SOC cell/stack with a methanation reactor). The physical interfaces between the experimental set-up (test station) and the system can be separated in media, electric, and heat interfaces. Media interfaces are the reactants inlet and products outlet. Water is supplied to the system as either steam or liquid water (vaporized within the system) at the mass flow rate of $q_{m,\text{H}_2\text{O},\text{sys},\text{in}}$, while CO_2 is supplied to the system at the volumetric flow rate of $q_{V,\text{CO}_2,\text{sys},\text{in}}$. The product gas with the volumetric flow rate of $q_{V,\text{product},\text{sys},\text{out}}$ contains mainly CH_4 , a small amount of other hydrocarbons ($\text{C}_n\text{H}_{2n+2}$, C_2H_6 , C_3H_8 , etc.), unreacted gas (CO , CO_2 , and H_2), and water vapour. Oxygen gas is also generated from the system at an apparent flow rate of $q_{V,\text{O}_2,\text{sys},\text{out}}$, while air (or oxygen) is frequently supplied to the system to carry O_2 generated at $q_{V,\text{O}_2,\text{sys},\text{in}}$ (oxygen flow rate) in the case of an oxide-ion conduction SOC. For a proton-conducting SOC, steam or a mixture of steam and inert gas is supplied as the positive electrode gas to carry the generated O_2 . The electric interfaces are the power supply (or load) and voltage wiring. The heat interface is the heat input/output to/from the system. These interfaces will be defined by different physical parameters. Depending on the test objective these physical parameters can be either of input nature (test input parameter, or TIP) or of output nature (test output parameter, or TOP).



IEC

Figure 2 – Schematic of the physical interfaces of the system

Measuring instruments used for testing the power-to-methane energy system shall meet the requirements of 6.2. The electric power input, heat input, heat output, flow rates (water, CO₂, O₂, sweep gas, product gas), fluid temperatures and pressures (water/steam, CO₂, O₂, sweep gas, product gas) and the product gas composition shall be measured.

Flow rates shall be evaluated at STP.

Further, the composition of product gas shall be measured to confirm the quality of methane. Additional measurements shall be performed based on the test parameters or test conditions or both.

Measuring instruments used for testing the components shall also meet the requirements of 6.2.

For the performance test of the SOC and the methanation reactor, see 7.3.1 and 7.3.2, respectively.

6.2 Instrument uncertainty

The expanded uncertainty of each measuring instrument (coverage factor $k = 2$) at the time of calibration or that estimated from the class of instrument shall meet the following requirements.

NOTE Coverage factor is defined in ISO/IEC Guide 98-3.

a) Instrument uncertainty for testing the power-to-methane energy system:

- electric power: ± 1 % of rated;
- temperature of fluids (gases, heat transfer fluid and water): $\pm 2,5$ K;
- pressure of gases: ± 1 % of rated;
- flow rate of heat transfer fluid: ± 2 % of rated;
- flow rate of water vapour: ± 2 % of rated;
- flow rate of methane, carbon dioxide oxygen and sweep gas: ± 2 % of rated;

- Gas composition:
 - ±2 mol % for H₂ and H₂O;
 - ±1 mol % for CO and CO₂;
 - ±0,3 mol % for O₂;
 - ±0,1 mol % for CH₄, C_nH_{2n+2} and N₂.

b) Instrument uncertainty for testing components:

- current: ±1 % of rated;
- voltage of the single cell in SOC: ±5 mV;
- temperature: ±2,5 K;
- gas flow rates: ±2 % of rated;
- gas pressures: ±1 % of rated;
- gas composition:
 - ±2 mol % for H₂ and H₂O;
 - ±1 mol % for CO and CO₂;
 - ±0,3 mol % for O₂;
 - ±0,1 mol % for CH₄, C_nH_{2n+2} and N₂.

6.3 Measurement methods

6.3.1 Measurement methods for testing the power-to-methane energy system

6.3.1.1 Electric power input

Electric power input measurement is used to calculate the electric energy consumption of the system over the test duration. Power meters, voltmeters, ammeters and other devices are used for the measurement.

For a three-phase system:

$$P_{AC} = \sqrt{3} \times V_{AC} \times I_{AC} \times \lambda \quad (1)$$

where

P_{AC} is the AC electric power supplied to the system (W);

V_{AC} is the AC voltage supplied to the system (V);

I_{AC} is the AC current supplied to the system (A);

λ is the power factor.

a) For a single-phase system:

$$P_{AC} = V_{AC} \times I_{AC} \times \lambda \quad (2)$$

where

P_{AC} is the AC electric power supplied to the system (W);

V_{AC} is the AC voltage supplied to the system (V);

I_{AC} is the AC current supplied to the system (A);

λ is the power factor.

b) For a DC power supply:

$$P_{DC} = V_{DC} \times I_{DC} \quad (3)$$

where

P_{DC} is the DC electric power supplied to the system (W);

V_{DC} is the DC voltage supplied to the system (V);

I_{DC} is the DC current supplied to the system (A).

6.3.1.2 Heat input

Fluid for transporting heat into the system may be water, oil, air or gas, etc. The flow rate and temperature of the heat transfer fluid shall be measured simultaneously to determine the heat input energy into the system. When steam generated outside the system is supplied to the SOC cell/stack, the heat energy for the vaporization of water and the temperature increase of steam, if any, shall be added to the heat input.

When using a gaseous medium, the pressure shall also be measured. Flow nozzles, orifices or venturi meters are recommended for the measurement of the heat transfer fluid flow rate. Mass flowmeters and turbine-type flowmeters can also be used. They shall be applied in accordance with ISO 5167-1.

The recommended instruments for the direct measurement of the heat transfer fluid temperature are thermocouples with transducer or resistance thermometers with transducer. Fluid temperature measuring devices shall be located near the boundary of the system. Fluid temperature sensors shall be placed directly in the fluid stream, in the middle of the cross-section of the pipe and shall not touch the pipe wall.

For pressure measurement, pressure gauge sensors shall be located just upstream of the associated flowmeter near the interface points in the fluid flow line. Adequate thermal insulation around pipes shall be used. Before the test, connecting piping shall be checked to ensure that the pipes are leak-tight under working conditions.

The heat energy input to the system shall be calculated by the following equation:

$$Q_{th, in} = \Sigma [(T_{H, out} - T_{H, in}) \times q_{V, H} \times \rho_H \times t_{dur} \times C_{p, c}] \quad (4)$$

where

$Q_{th, in}$ is the heat energy input to the system over the test duration (kJ);

$T_{H, out}$ is the temperature of the heat transfer fluid output (K);

$T_{H, in}$ is the temperature of the heat transfer fluid input (K);

$q_{V, H}$ is the volumetric flow rate of the heat transfer fluid (m³/s);

ρ_H is the density of the heat transfer fluid at measured pressure and temperature (kg/m³);

$C_{p, c}$ is the specific heat capacity of the heat transfer fluid at standard pressure (kJ/(kg · K));

t_{dur} is the measurement duration (s).

If the heat transfer fluid is a mixture, analyse the composition and calculate the specific heat capacity of the mixture by the following equation:

$$C_{p,c} = \sum (x_{m,i} \times C_{p,i}) \quad (5)$$

where

$C_{p,c}$ is the specific heat capacity of the heat transfer fluid at standard pressure (kJ/(kg · K));

$x_{m,i}$ is the mass fraction of component i ;

$C_{p,i}$ is the specific heat capacity of component i at standard pressure (kJ/(kg · K));

6.3.1.3 Sweep gas input

The flow rate, temperature, composition (O₂ concentration), and pressure of the sweep gas at the inlet of the system shall be measured.

6.3.1.4 Methane output

The flow rate, temperature, composition, and pressure of the product gas shall be measured concurrently to determine the system performance. Further, the quality of the product methane shall be confirmed by measuring impurities and purity.

The flow rate shall be measured using mass flowmeters, volumetric flowmeters or turbine-type flowmeters. The flowmeter shall be selected by taking into consideration the range of flow rates and the allowable uncertainty of the flowmeter. When measurements are made on a volumetric basis, they shall be converted to volumetric flow rate at STP by measuring the gas temperature and pressure or gas density close to the flowmeters. The measurement uncertainty shall be evaluated in accordance with ISO 5168 or ISO 7066-2.

Besides methane, the product gas includes small quantities of hydrogen, carbon monoxide, carbon dioxide, hydrocarbons (C_nH_{2n+2}), and water. The components shall be measured according to the methods detailed in the ISO 6974 series, ISO 6975, the ISO 10101 series and ISO 11541. The product gas shall be sampled during the operation of the system with an appropriate number of samples.

For the direct measurement of temperature, thermocouples with transducer or resistance thermometers with transducer are recommended. The sensor shall be installed just upstream of the flow measurement device.

For the measurement of pressure, manometers, dead-weight gauges, Bourdon tubes or other elastic type gauges can be used.

Connecting piping shall be checked to be leak-tight under working conditions before the test. If pressure fluctuations occur, a suitable means of damping shall be used in an effective position.

6.3.1.5 Heat output

The fluid for recovering heat from the system may be water, air or coolant such as oil. The flow rate and temperature of heat transfer (recovery) fluid shall be measured concurrently to determine the heat output energy from the system. Further, in case of a gaseous medium, the pressure shall also be measured.

Flow nozzles, orifices or venturi meters are recommended for the measurement of the heat transfer fluid flow rate. Mass flowmeters and turbine-type flowmeters can also be used. They shall be applied in accordance with ISO 5167-1.

Recommended instruments for the direct measurement of the heat recovery fluid temperature are thermocouples with transducer or resistance thermometers with transducer. Fluid temperature measuring devices shall be located near the boundary of the system. Fluid temperature sensors shall be placed directly in the fluid stream, in the middle of the cross-section of the pipe and shall not touch the pipe wall.

For pressure measurement, pressure gauge sensors shall be located just upstream of the associated flowmeter near the interface points in the fluid flow line. Adequate thermal insulation around pipes shall be used. Before the test, connecting piping shall be checked to ensure that the pipes are leak-tight under working conditions.

The heat energy output from the system shall be calculated in the same way as in 6.3.1.2.

6.3.1.6 Sweep gas output

The flow rate, temperature, composition (O_2 concentration), and pressure of sweep gas at the outlet of the system shall be measured.

6.3.1.7 Dew point temperature

When it is necessary to measure the dew point (humidity) of a gas, a dew point meter, water content meter, or gas chromatograph shall be used, while controlling the gas temperature to prevent condensation of water vapour.

6.3.2 Measurement methods for testing components

6.3.2.1 General

The testing components that are to be tested in the system are a SOC cell/stack assembly unit and a methanation reactor (see Figure 1 and Figure 2). The SOC single cell consists of the solid oxide electrolyte sandwiched between the positive and negative electrodes. For the case of a SOC operated as a SOFC or in reversible mode, measurement methods are described in IEC 62282-8-101 (SOEC to produce H_2 only as well as SOFC operation mode and reversible mode) and IEC 62282-7-2 (SOFC mode only).

6.3.2.2 Negative electrode gas

6.3.2.2.1 Negative electrode gas flow rate

The flow rates of the negative electrode supplied gas and product gas shall be measured by using mass flowmeters, volumetric flowmeters or turbine-type flowmeters. Measures shall be taken to prevent condensation of water vapour. The flowmeter shall be selected by taking into consideration the species of the gases, the range of flow rates, and the allowable uncertainty of the flowmeter. When measurements are made on a volumetric basis, they shall be converted to volumetric flow rate at STP by measuring the gas temperature and pressure or gas density close to the flowmeters. The measurement uncertainty shall be evaluated in accordance with ISO 5168, ISO/TR 7066-1 or ISO 7066-2.

6.3.2.2.2 Negative electrode gas composition

The compositions of the negative electrode supplied gas and product gas shall be measured when the performance of the cell/stack assembly unit is measured. However, if it is not possible to measure the supplied gas compositions, the supplied gas composition shall be measured during the preparation of the performance test under the same conditions as those of the unit performance test.

When the negative electrode gas is supplied by mixing component gases in a controlled manner using multiple flowmeters, the composition can be calculated based on the values obtained from each flowmeter, in accordance with ISO 6145-7.

The supplied gas and the product gas shall be sampled near the gas inlet and the gas outlet of the cell/stack assembly unit, respectively, and analysed using an infrared spectrometer, mass spectrometer, gas chromatograph or similar device. A dew point meter or a hygrometer may also be used to measure the water vapour concentration. The gas sample shall be transported from its origin to the point of analysis in a manner which minimizes changes in composition. Thus, the material, temperature, diameter and the length of the tubing shall be carefully chosen to minimize the compositional change in the sampling tube. As necessary, the tube shall be heated to avoid condensation of water vapour.

If water vapour is likely to affect the measurement, water vapour shall be removed from the gas sample after measuring its concentration. Alternatively, the gas sample shall be diluted with an inert gas.

The gas analyser shall be calibrated using a standard gas of known mass ratio, temperature, and pressure.

The measurement uncertainty shall be evaluated in accordance with the ISO 6974 series, ISO 6141, ISO 6142-1, or ISO 6143.

6.3.2.2.3 Negative electrode gas temperature

The temperature of the negative electrode gas shall be measured near the gas inlet and the gas outlet of the cell/stack assembly unit by using a thermocouple or sheathed thermocouple and an extension lead-wire of a type and class in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515.

NOTE There can be significant differences between the temperature of the tube wall and the temperature of the bulk gas.

6.3.2.2.4 Negative electrode pressure

The pressure of the negative electrode gas shall be measured upstream of the gas inlet and downstream of the gas outlet of the cell/stack assembly unit by using a calibrated pressure sensor, manometer, Bourdon tube or similar instrument. The measuring instrument shall be located in such a manner that the uncertainty is minimized considering pressure losses in the pipe, the pipe temperature and other factors. Ensure that there is no condensation of water vapour during the measurement. One way to prevent the condensation can be to measure the pressure by injecting a very small amount of dry nitrogen gas or similar into the pipe, close to the measuring instrument.

6.3.2.3 Positive electrode gas

6.3.2.3.1 Positive electrode gas flow rate

The flow rates of the positive electrode supplied gas and product gas shall be measured by using mass flowmeters, volumetric flowmeters or turbine-type flowmeters. When measurements are made on a volumetric basis, they shall be converted to volumetric flow rate at STP by measuring the gas temperature and pressure or gas density close to the flowmeters. The flowmeter shall be selected in consideration of the expected range of flow rates and the allowable uncertainty of the flowmeter. The uncertainty shall be evaluated in accordance with ISO 5168, ISO/TR 7066-1 or ISO 7066-2.

6.3.2.3.2 Positive electrode gas composition

For the compositions of the positive electrode supplied gas and product gas, the oxygen concentration shall be measured using a gas chromatograph or an oxygen concentration meter. The positive electrode gas shall consist of clean (oil-free), compressed air or bottled gas. If a bottled gas mixture is used, the values described on its composition certificate published by the gas supplier can be used. The uncertainty of the instrument shall be evaluated in accordance with the ISO 6974 series, ISO 6141, ISO 6142-1, ISO 6143 or ISO 6145-7.

When it is necessary to measure the water vapour concentration, a dew point meter, a hygrometer or a gas chromatograph shall be used while controlling the gas temperature to prevent condensation of water vapour.

6.3.2.3.3 Positive electrode gas temperature

The temperature of the positive electrode gas shall be measured near the gas inlet and the gas outlet of the cell/stack assembly unit by selecting a thermocouple or sheathed thermocouple, and an extension lead-wire of the type and class that are appropriate in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515.

NOTE There can be significant differences between the temperature of the tube wall and the temperature of the bulk gas.

6.3.2.3.4 Positive electrode gas pressure

The pressure of the positive electrode gas shall be measured upstream of the gas inlet and downstream of the gas outlet of the cell/stack assembly unit by using a pressure sensor, manometer, Bourdon tube, or similar. The measuring instrument shall be located in such a manner that the uncertainty is minimized in consideration of any pressure loss within the piping, piping temperature, and other factors.

6.3.2.4 Input voltage

A voltage meter shall be connected to the voltage measuring points specified by the manufacturer in order to measure the cell/stack assembly voltage. The connecting cable shall be durable enough for the test conditions. Ensure that there is no thermoelectromotive force at the connection.

6.3.2.5 Input current

The input current shall be measured by a suitable ammeter, considering the current range, or alternatively by measuring the voltage across a known shunt resistor in the input current circuit. The measurements shall be sent to a suitable recording instrument/system. The connecting cables shall be selected with appropriate size, materials and geometry in consideration of the test conditions and voltage drop within the cables.

6.3.2.6 Cell/stack assembly unit temperature

Thermocouples or sheathed thermocouples and extension lead-wires of the type and class that is appropriate shall be selected in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515. They shall be placed at the temperature measuring points and connected with a recorder or similar for measurement. When there are more than one temperature measuring points in the cell/stack assembly unit, the unit temperature and its distribution shall be obtained by the calculation method recommended by the manufacturer.

6.3.2.7 Mechanical load

A mechanical load, if necessary, applied to the cell/stack assembly shall be measured, for example by a load cell.

6.3.2.8 Area-specific resistance

The area-specific resistance (R_{ASR}) of the cell/stack assembly unit is defined as the differential slope of the current-voltage curve (dV_{cell}/dJ or dV_{stack}/dJ) at a specified voltage (voltage of the cell V_{cell} or voltage of the stack V_{stack}) and current density J . It is determined by linear regression of at least three data points around the target voltage or current density value, obtained on the ascending part of the current-voltage curve. It is recommended that the selected voltage or current density values should lie within the apparent linear regime of the polarization curve. If they do not, then the selected voltage values should lie in a very small window (typically less than 10 mV) for which the voltage response to the current density change may be considered as linear. The ASR shall be directly measured as the ohmic and non-ohmic resistances by either the AC impedance method according to IEC 62282-8-101:2020, Annex B or the current interruption method according to IEC 62282-7-2:2021, 10.7.2.3. An appropriate measuring cable shall be used in order to ensure high-quality data over the entire frequency range investigated.

See IEC 62282-8-101:2020, 7.2.3, Annex B.

6.3.2.9 Ambient conditions

In defining the ambient conditions, the ambient temperature, pressure, and relative humidity shall be measured. The sampling interval shall be the value specified in ISO 8756 or less.

6.3.2.10 Methanation reactor gas

The temperature, flow rate, pressure and gas composition are measured at the inlet and outlet of the whole system and can be measured at the inlet and outlet of the methanation reactor, if applicable. These measured values are used to calculate the conversion and carbon balance described in 7.3.2.

The temperature of the gas is measured by a thermocouple inserted in the gas flow channel. The pressure of the gas is measured by a pressure sensor inserted in the gas flow channel or in the branch channel. The gas flow rate is measured by a mass flowmeter or a conventional areal flowmeter attached to the gas flow channel. In order to measure the composition of the gas, a small portion of the gas collected from the gas channel by appropriate sampling methods (for example, by a gas sampling bag, a gas-tight syringe or a gas-sampling loop) is measured by a gas chromatograph. If necessary, the water vapour contained in the outlet gas is removed by condensation.

7 Test methods and procedures

7.1 General

In this Clause 7, the test methods and procedures for the power-to-methane system (SOC cell/stack assembly with a methanation reactor) are described. The test methods for a SOC cell/stack operated as a SOFC including reversible operation (without any methanation reactor) are already described in IEC 62282-8-101. Users can substitute the selected test methods of this document with equivalent test methods given in IEC 62282-8-101 (SOEC to produce H_2 only as well as SOFC operation mode and reversible mode) and IEC 62282-7-2 (SOFC mode only).

7.2 System performance tests

7.2.1 Start-up test

In this test, the start-up time and the energy (heat and electric energy) required for the start-up of the system is measured.

$$E_{\text{st}} = E_{\text{el, in}} + Q_{\text{th, in}} \quad (6)$$

where

E_{st} is the start-up energy (kJ);

$E_{\text{el, in}}$ is the electric energy input to the system (kJ);

$Q_{\text{th, in}}$ is the heat (thermal) energy input to the system (kJ).

Before starting the test, keep the system in the cold state for a minimum of 24 h or until the temperature of the SOC stack and the temperature of the methanation reactor is below ambient temperature +20 K. Then, start the test, and record the time when the start-up action is commenced. Measure the heat and electric energy input/output, the temperature of the SOC and of the methanation reactor, and flow rates of water, CO₂, and product gas with their temperatures, pressures and compositions at intervals of 10 min or less. The measurement shall be continued until the gas production rate of the system reaches 90 % of the rated value. If the production rate is less than 90 % of the rated value, the methane concentration shall reach a stable value (not more than 2 mol % deviation between two subsequent measurements at the interval of 10 min).

The start-up conditions, such as heating rate and test environment conditions during the heating ramp shall be based on those recommended by the manufacturer or the results of preliminary tests.

NOTE 1 The initiation of a start-up is the time when the start-up button is pressed or the normal start-up signal is sent.

NOTE 2 The completion of a start-up is the time when the methane production rate reaches the rated value.

NOTE 3 The "90 % of the rated value" is based on the assumption that the system degrades with operation.

7.2.2 Performance tests at rated operation

7.2.2.1 General

The tests shall be carried out according to the following procedure:

- a) operate the system at the rated conditions;
- b) verify that the system is in a stable state;
- c) measure the system operating parameters including power input, heat input, heat output, product gas flow rate, pressure and composition at intervals of 10 min or less.

7.2.2.2 Rated production rate of methane

In this test, the production rate of methane under rated conditions is evaluated by the following method.

The rated conditions of the system recommended by the manufacturer shall be verified before the test. Further, the measurement conditions and stable state conditions for the testing shall be determined.

The rated production rate of methane is calculated using the following equation:

$$q_{V, \text{CH}_4, \text{ sys, out}} = x_{\text{CH}_4, \text{ sys, out}} \times q_{V, \text{product, sys, out}} \quad (7)$$

where

- $q_{V,CH_4,sys,out}$ is the volumetric flow rate (volumetric production rate) of CH_4 at the outlet of the system at STP (m^3/s);
- $x_{CH_4,sys,out}$ is the molar fraction of CH_4 in the product gas at the system outlet (mol/mol);
- $q_{V,product,sys,out}$ is the total volumetric flow rate of product gas at the outlet of the system (at STP) (m^3/s).

7.2.2.3 Conversion of CO_2 into CH_4

The conversion of carbon dioxide into methane (y_{CH_4/CO_2}) in the system is defined as the ratio of the volumetric flow rate of CH_4 at the outlet of the system ($q_{V,CH_4,sys,out}$) to that of CO_2 supplied to the system. The conversion of CO_2 into CH_4 shall be calculated by the following equation:

$$y_{CH_4/CO_2} = \frac{q_{V,CH_4,sys,out}}{q_{V,CO_2,sys,in}} \times 100 \quad (8)$$

where

- y_{CH_4/CO_2} is the conversion of CO_2 into CH_4 (%);
- $q_{V,CH_4,sys,out}$ is the volumetric flow rate of CH_4 at the outlet of the system (m^3/s);
- $q_{V,CO_2,sys,in}$ is the volumetric flow rate of CO_2 at the inlet of the system (m^3/s).

7.2.2.4 Mass balance evaluation

Because solid carbon can frequently be deposited in the system (SOC cell/stack, methanation reactor, and piping), an evaluation of the mass balance of carbon is very important. The mass balance of carbon is defined as the ratio of molar flow rate of carbon-containing species ($CH_4 + CO + CO_2$) at the outlet of the system to that of total carbon-containing species (usually CO_2 only) supplied to the system. The thermodynamic condition for carbon deposition shall be determined and steam levels adjusted to ensure carbon deposition is not thermodynamically favoured. The mass balance of carbon (%) shall be calculated by the following equation:

$$\text{Carbon mass balance [\%]} = \frac{(x_{CH_4,sys,out} + x_{CO,sys,out} + x_{CO_2,sys,out} + \sum_n n \times x_{C_nH_{2n+2},sys,out}) \times q_{V,product,sys,out}}{q_{V,CO_2,sys,in}} \times 100 \quad (9)$$

where

- $x_{CH_4,sys,out}$ is the molar fraction of CH_4 at the outlet of the system (mol/mol);
- $x_{CO,sys,out}$ is the molar fraction of CO at the outlet of the system (mol/mol);
- $x_{CO_2,sys,out}$ is the molar fraction of CO_2 at the outlet of the system (mol/mol);
- $x_{C_nH_{2n+2},sys,out}$ is the molar fraction of hydrocarbon gas (for example, $n = 2$, C_2H_6) other than methane at the outlet of the system (mol/mol);
- $q_{V,product,sys,out}$ is the total volumetric flow rate of product gas (CH_4 -containing gas) at the outlet of the system (m^3/s);
- $q_{V,CO_2,sys,in}$ is the volumetric flow rate of CO_2 at the inlet of the system (m^3/s).

7.2.2.5 Heat balance evaluation

In order to evaluate the heat balance of the system, both rates of heat input and output shall be measured separately.

The heat input rate is the thermal power, which is absorbed by the tested system during the system operation at the different operation modes of the SOC (SOEC-mode and SOFC-mode). The heat input is fed to the system by using a heat transfer fluid [e.g. water or gas (steam, CO₂) or both].

The heat output rate is the usable thermal power output, which is recovered by the tested system during the system operation at the different operation modes of the SOC. Because the methanation reaction is an exothermic reaction (252,96 kJ/mol, higher heating value), a heat output is expected besides its use for generating steam for the SOC (vaporization heat 40,00 kJ/mol; 80,00 kJ for two moles of H₂O). The heat output is extracted from the system by using a heat transfer fluid. The heat output rate does not include waste heat losses, for example due to system components cooling.

The heat balance is calculated as follows:

$$\Delta P_{\text{th, sys}} = P_{\text{th, sys, out}} - P_{\text{th, sys, in}} \quad (10)$$

where

$\Delta P_{\text{th, sys}}$ is the heat balance of the system;

$P_{\text{th, sys, out}}$ is the sum of the heat output rate of all the heat transfer fluids of the system;

$P_{\text{th, sys, in}}$ is the sum of the heat input rate of all the heat transfer fluids of the system.

7.2.2.6 Specific electric energy

In this test, the specific electric energy of the system under rated conditions is evaluated by the following method.

The specific electric energy of the system is calculated using the following equation:

$$E_{\text{sp, CH}_4} = \frac{P_{\text{AC}} + P_{\text{DC}}}{q_{V, \text{CH}_4, \text{ sys, out}}} \quad (11)$$

where

$E_{\text{sp, CH}_4}$ is the specific electric energy consumed for producing a unit volume of CH₄ (kJ/m³);

P_{AC} is the AC electric power supplied to the system (kW);

P_{DC} is the DC electric power supplied to the system (kW);

$q_{V, \text{CH}_4, \text{ sys, out}}$ is the volumetric flow rate (volumetric production rate) of CH₄ at the outlet of the system at STP (m³/s).

NOTE $E_{\text{sp, CH}_4}$ (kJ/m³) can be converted into the unit of kWh/m³ by dividing it by 3 600.