CAST 2 Combustion Aerosol Standard

- **Real combustion particles for calibration and filter material testing**
- **Rapid adjustable mobility particle diameter range from 30 ... 200 nm**
- **Monomodal and bimodal particle size distributions**
- **Modular set-up with and without adjustable diluter**
- **Easy stand alone and PC linked operation**

INTRODUCTION

The increasing knowledge about adverse health effects by submicron particles from fossil fuel combustion has accelerated the development of new methods characterizing such particles, the commercial availability of corresponding new instrumentation and the introduction of particle filters preventing pollution of our environment by these nanoparticles.

Soot particle measuring devices require test aerosols for calibration which are adjustable in concentration and size with high reproducibility and long term stability. Test aerosols are also needed to test the precipitation characteristics of particle filter materials. Such test aerosol should be as similar as possible to soot particles in morphology and chemical composition. CAST 2, a second generation soot generator and calibrator based on the development of a soot burner by Dr. Jing at METAS (Swiss Federal Institute for Metrology and Accreditation) is in compliance with these demands.

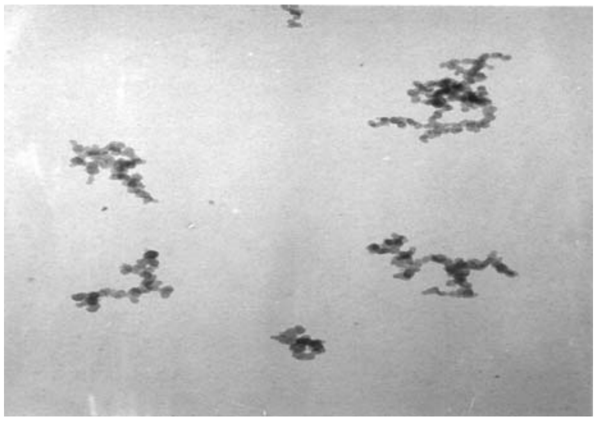

Fig. 1 TEM image from CAST soot particles

A special burner construction and gas control allows the generation of suspended particles in a wide size- and concentration range with a reproducibility of typically +/- 5 %. Their chemical composition and morphology is similar to those emitted from real combustion processes especially like diesel engines.

The generator is built up in a rugged 19" case for rack mounting or stand alone use. It is supplied with C_3H_8 fuel gas and N_2 from external gas bottles and compressed air.

The novelty of CAST 2 with respect to the previous generation CAST system is in its modular set up and stand alone operation without PC as well as PC linked operation. New burner construction and sampling facilities open additional applications. CAST 2 can optionally be connected to closed systems with differential pressures to atmosphere from –100 to + 300 mbar. Using as a calibrator in combination with the MD19 rotating disk diluter improved stability and reproducibility are achieved for calibrating size and number by the following upgrade: The absolute pressure inside the burner is regulated to an absolute pressure of 1050 mbar. This feature compensates any influence atmospheric pressure variations (height above see level, meteorological variations) on the soot formation in the burner.

APPLICATIONS

CAST is an ideal tool to calibrate and adjust nanoparticle sensors and measuring systems which characterize particles in number-, surface-, mass-concentration, size and elemental carbon (EC). Connection to closed systems with differential pressures to ambient conditions enable the user to test filter materials on their precipitation characteristics depending on particle size.

PRINCIPLE OF SOOT PARTICLE GENERATION

The principle of CAST presented here consists primarily in soot particles formed in a co-flow diffusion flame of hydrocarbon by preventing further oxygenation in the flame above a certain flame height. In the next step flame aerosol is mixed with quenching gas in order to prevent further combustion processes in the particle stream and to stabilize the soot particles.

Fig. 2 illustrates the construction of the flame unit. The gaseous fuel stream is concentrically surrounded by a stream of dry and particle free oxidation air. In order to produce soot particles, the symmetrical diffusion flame is wrapped with a, tapering upward, circular truncated cone of steel. A position for the truncated cone is found whereby the smoke column withdraws from the upper opening of the combustion chamber despite the burning flame. In a certain flame height the oxidation air is insufficient for further oxiditation of the generated soot particles. Leaving the combustion chamber by the upper opening, they are wrapped by exhaust gases which develop around the flame what prevents the particle stream from depositing at the device walls. In a pipe arranged perpendicular to the flame axis N_2 is supplied to the particle stream to quench further combustion processes and stabilize the soot particles.The quenching inhibits condensation in the particle stream when it escapes from the flame unit of ambient air condition. To dilute the particle stream, compressed air is supplied through the gap between the two concentrical pipes.

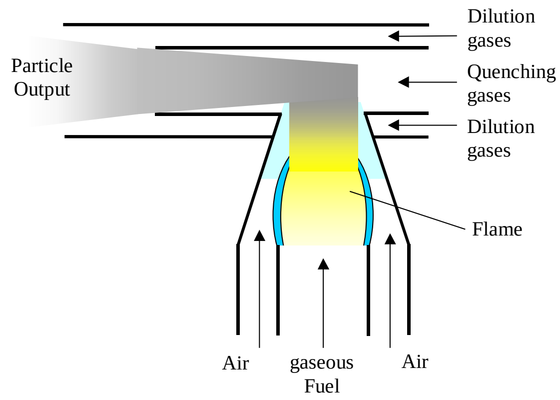

Fig. 2 burner unit

Soot particles with monomodal size distribution are generated in the flame unit and their mean diameter can be controlled by the flows of the different input gases. The variation of the mean particle size is mainly done by tuning the dilution of the C_3H_8 fuel gas with admixed N_2 and variation of the oxidation air flow. A mean mobility diameter range from 30 to 200 nm is adjustable by variation of these flows.

CAST generates soot particles with high stability and reproducibility in size and number concentration. These excellent characteristics are achieved by the following features in the construction and gas control of the generator.

- Defined pure gases from standard gas cylinder and precision mass flow controllers are used for the flame.
- The combustion chamber is shielded from the environment and a dilution is realized which suppresses influences from the environment conditions.
- The laminar concentrical flows of the (exhaust) gases which develop around the flame generate a sheath around the particle stream which prevents deposition of soot on the inner walls of the flame unit.

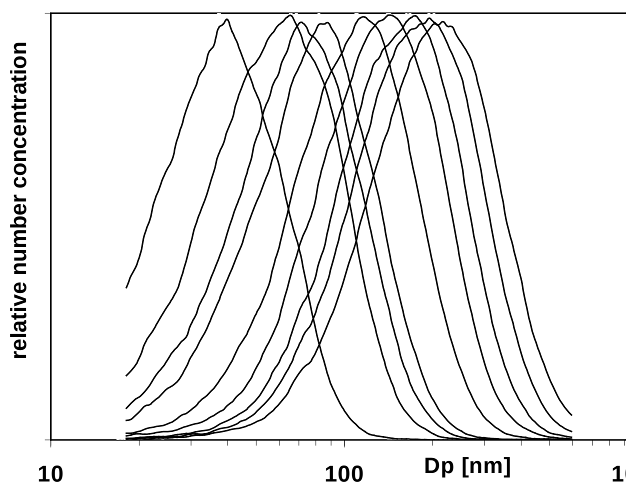

Fig. 3 shapes of monomodal SMPS size distributions

PNEUMATIC BLOCK DIAGRAM OF CAST 2

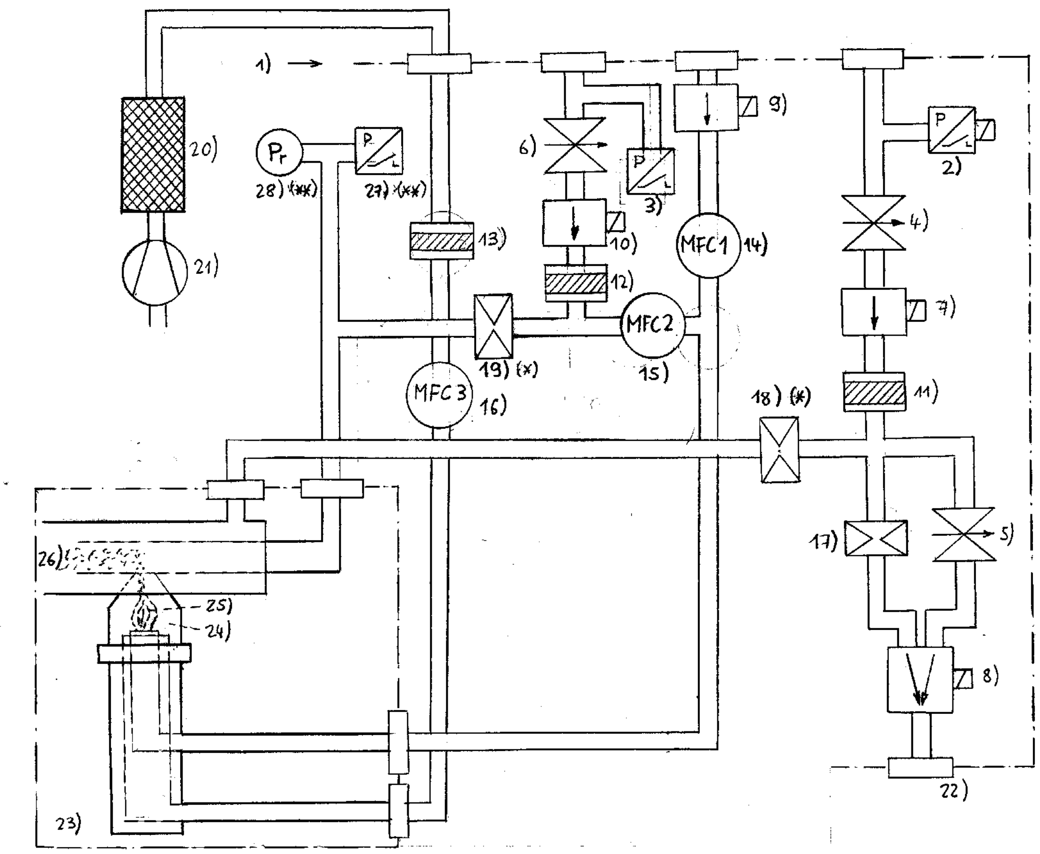

Fig. 4   pneumatic block diagram of CAST 2

Legend

1) Encoded pluggable gas connectors
2) Compressed air pressure control
3) Nitrogen pressure control
4) Pressure reducing valve for compressed air
5) Flow adjustment valve for diluter cleaning air
6) Pressure reducing valve for nitrogen
7) 2/2-way valve for compressed air
8) 3/2-way valve for MD19-diluter cleaning air
9) 2/2-way security valve for fuel gas
10) 2/2-way valve for nitrogen
11) Particle filter for MD19- and burner dilution air
12) Particle filter for nitrogen
13) Particle filter for oxidation air
14) Mass flow controller (MFC 1) for fuel gas
15) MFC 2 for nitrogen mixing gas
16) MFC 3 for oxidation air
17) Critical orifice for MD19-dilution air
18) Critical orifice for burner dilution air
19) Critical orifice for nitrogen quenching gas
20) Silica gel drier for oxidation air
21) Pump for oxidation air
22) Dilution air output for optional MD19-diluter
23) Soot burner unit
24) Combustion chamber
25) Co-flow diffusion flame
26) Test aerosol output to sampling tube or MD19-diluter
27) Unit for pressure control inside burner to initiate an emergency stop in case of overpressure
28) Sensor for relative pressure to atmosphere inside burner

(*) Orifices are replaced by mass flow controllers when CAST 2 is optionally specified with pressure compensation

(**) Pressure sensor and –control for optional pressure compensation

SAMPLING CONNECTIONS TO CAST 2 BURNER

Assembly for undiluted test aerosol sampling

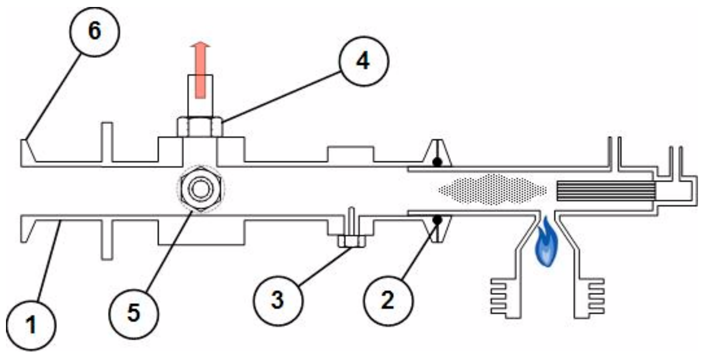

Fig. 5 undiluted test aerosol sampling tube

1) Stainless steel sampling tube
2) Sealed connection to burner output
3) Temperature sensor for flame detection
4) Pneumatic connector to excess soot filter and pump
5) 12 mm Swagelok user connection for partial flow sampling
6) User connection with flange DN 32-40 ISO for total flow sampling

Standard setup for undiluted test aerosol sampling

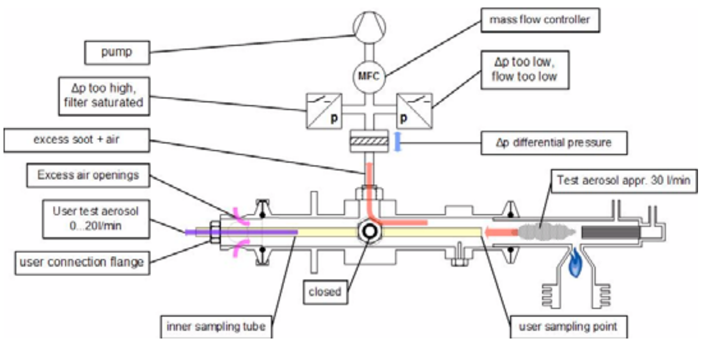

Fig. 6 partial flow test aerosol sampling at atmospheric pressure conditions

Connection for sampling at atmospheric pressure conditions where the user defines the sample flow in the range from 0 – 20 ln/min.

A fraction (0 – 20 ln/min) of the total flow from the burner (appr. 30 ln/min) is sampled at the user connection, a stainless steel tube with 12 mm outer diameter.

40 ln/min are drawn by the pump through the particle filter. The difference between these 40 ln/min and the flow sampled by the user enters through the openings in the user connection flange and dilutes the excess soot through the particle filter.

2 pressure control units examine the deposition of soot on the particle filter (Δp too high) and the correct flow through the filter (Δp too low).

The user sampling point close to the burner output prevents the dilution of the user test aerosol.

Setup for adjustable partial test aerosol flow in sealed connection

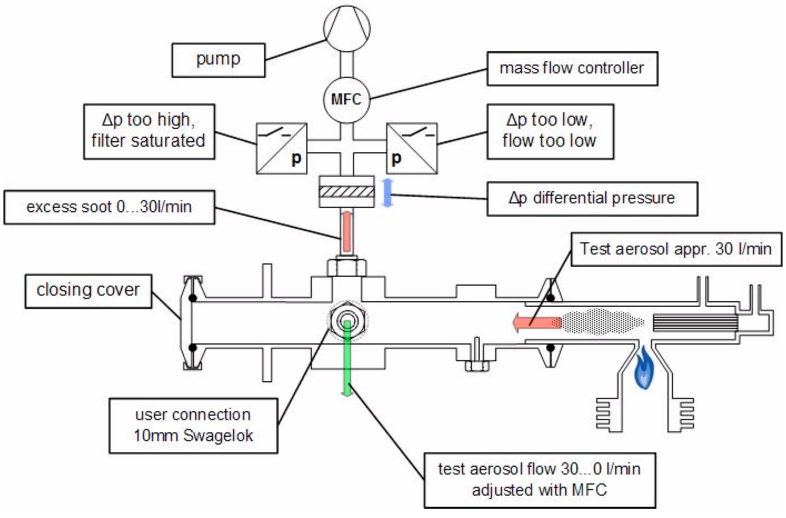

Fig. 8 partial flow test aerosol sampling in sealed connection

Sampling in sealed connection allowing back pressures up to 300 mbar where the partial test aerosol sampling flow is adjusted in the CAST 2 PC software.

The total flow from the burner is split into two fractions, the test aerosol on the user connection, a stainless steel tube with outer diameter 10 mm, and the excess soot through the particle filter.

The test aerosol flow as the difference between the total flow from the burner and the excess soot flow is adjusted by the mass flow controller within the range 0 – 30 ln/min.

This application allows back pressures up to 300 mbar in relation to atmospheric conditions.

Optional pressure compensation compensates the pressure influence on the gas flows into the burner.

Differential pressure to atmosphere is controlled for safety reasons and measured to enable additional compensations in the soot generation.

Setup for sampling from adjustable diluter

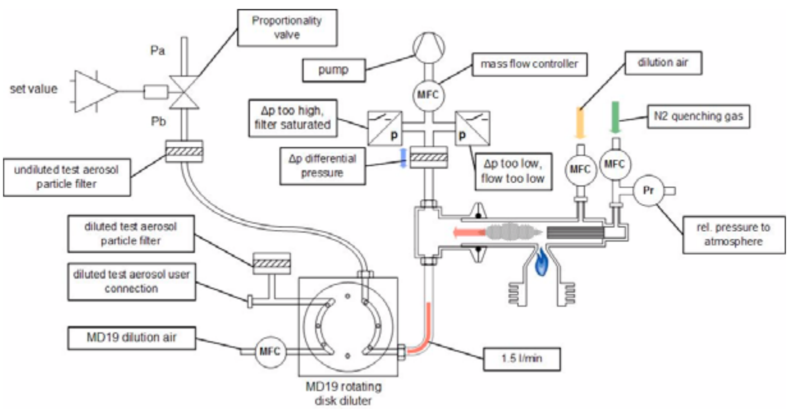

Fig. 9 diluted test aerosol sampling

This sampling setup is designed for calibration of nanoparticle measuring instrumentation. The rotating disk diluter allows to set the number concentration of the test within a range of appr. 10^3 -–10^7 $cm^{-3.}$

Highest accuracy and reproducibility in number concentration is achieved when the absolute pressure inside the burner is kept on a stable value independent from atmospheric pressure variation (wether conditions, sea level) and other influences.

An optional control to stabilize the absolute pressure on 1050 mbar is realized using a proportionality valve connected to the undiluted gas output of the diluter

Atmospheric pressure P_a and relative pressure P_r to P_a are individually measured in CAST 2. P_r can be varied by the position of the electronically controlled proportionality valve and is adjusted by software to stabilize $P_r + P_a$ to 1050 mbar.

The diluted test aerosol is sampled at atmospheric conditions in a flow range from 0.5 to 4 l/min. The flow is defined by the connected instrumentation under test.

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PRINCIPLE OF OPERATION

The principle of operation is explained following the pneumatic block diagram Fig. 4.

Burner

Size and concentration of the soot particles generated in the burner 23) depend on the mixing ratio of five gases. Three of them, oxidation air, nitrogen mixing gas and fuel gas are mass flow controlled in high stability precision mass flow controllers MFC 1, MFC 2 and MFC 3. The flows of the burner dilution air and the N_2 quenching gas are adjusted by critical orifices 18) and 19) since they are not varied in operation. The critical orifices 18) and 19) are replaced by mass flow controllers to keep the mass flows independent of the pressures when CAST 2 is optionally specified for pressure compensation. The specified input pressures for compressed air and N_2 are controlled with pressure control switches 2) and 3). The security valve 9) on the fuel gas input only remains open after a start routine when the flame in the burner 23) is detected by the temperature sensor in the sampling assembly within a certain time before timeout.

Additional security is provided by an internal fuel gas detector which initiates a gas alarm at a first detection level and an emergency stop with closure of all gas inputs at a second increased level. Safety stop is also initiated by an “Emergency stop” push button and in case of overpressure inside the burner.

Stable operation of the burner in particle size requires oxidation air with a stable N2/O2 mixing ratio as it is only ensured in ambient air and a low humidity below 1% r.h. at 23 °C. It must also be free from organic chemical compounds which can be present in compressed air systems. The oxidation air is therefore sampled from ambient air by the pump 21) and conditioned in the silica gel drier 20) and particle filter 13).

Sampling, Dilution

The nanoparticles escaping from the burner output 26) with number concentrations in the order of 10^8 ... 10^9 part./cm^3 at a total flow of 30 ln/min can be sampled in different ways as explained in the previous chapter:

- Without dilution. The burner dilution air and N2 quenching gas ensure that the aerosol from the burner unit is kept below the dew point.
- With additional dilution in the optional rotating disk diluter MD19-1iC within an adjustable dilution ratio from 1:50 to 1:10'000

In most sampling modes only a fraction of the total aerosol flow from the burner is sampled by the user. The excess soot as the difference between total and sampled flow is drawn by a pump through a particle filter. It has to be ensured that this excess soot sampling is working properly and the excess soot particle filter is not overloaded. Two pressure control switches examine

- on a lower set point whether the excess soot pump is working properly or
- on an upper set point whether the pressure drop over the particle indicates that the filter package has to be replaced.

Control, Operation

The entire CAST 2 system is controlled from a microprocessor control unit. It is operated stand-alone with the help of push buttons, signal LED’s and a 4 digit alphanumeric LED display. A link to PC via RS 232 serial interface allows

- Loading of configurations and menus
- Operation on PC with an optional PC software for extended applications.

A number of system controls provide a safe and reliable operation with detection of errors or unspecified conditions to minimize the risk of malfunction.

The entire modular CAST 2 system is mounted in a 19” laboratory case and is designed for operation in a well ventilated laboratory or test area environment.

TECHNICAL SPECIFICATIONS

Aerosol	Soot particles generated in C_3H_8-diffusion flame (propane)
Elemental carbon (EC) fraction	Particle diameter 30 nm: 75 %, 100 nm: 97 %, 200 nm: 99 %
EC concentration in test aerosol from burner	Particle diameter 30 nm: appr. 4 mg/m^3 Particle diameter 100 nm: appr. 60 mg/m^3 Particle diameter 200 nm: appr. 350 mg/m^3
Number concentration test aerosol from burner	10^8 .... 10^9 part./cm^3
Number concentration from optional adjustable MD19-1i-diluter	10^3 .... 10^7 part./cm^3 adjustable on scaled 10-turn potentiometer or with PC
Size distribution	monomodal, bimodal
Adjustable test aerosol size distributions	6 monomodal distributions with mode diameter from 30 ... 200 nm 1 bimodal distribution with mode diameters at appr. 35 and 180 nm
Reproducibility	+/- 5% in concentration +/- 5% +/- 3 nm in particle size for sampling with optional diluter
Test aerosol flow from burner	1 .... appr. 30 l/min
Test aerosol flow from opt. Diluter	0.3 ....4 l/min
Optional pressure compensation	Up to 300 mbar
Gas Specifications	C_3H_8 (propane), purity 99,95 % N_2, purity 99,999 % dry (< 10% r.h. at 23 °C) and oil free compressed air
Security	Flame detection by temperature sensor in burner Hard- and software prevent independently operation if flame is not detected Gas detector inside CAST initiates gas alarm and emergency stop
Operation and control	Stand alone by microprocessor control unit On PC with optional LabView software
Communication	Via RS 232 serial interface
Operating temperature	T_{amb}: 10 .... 30 °C
Case	9HE-19"-case, dimension appr. 510x400x500 mm (WxHxD)
Weight	Appr. 40 kg
Supply	90 - 260 V AC, max. 70 VA (without diluter), max. 120 VA (with diluter)
Accessory (included)	separate pump for excess soot 3 metallic shielded gas tubes length 2 m to compressed air and gas bottles with plugable and encoded gas connectors on CAST 2 side 1 RS 232 cables, length 3m with 9 pol D-Sub connector spare filter cartridges for test aerosol and excess soot CD-Rom with CAST 2 service and configuration software CAST 2 operation handbook several small accessories for maintenance, service and tests wooden transportation box for CAST 2 (80 x 74 x 64 cm) gross weight with CAST 69 kg carrying case for accessories (65 x 45.5 x 23 cm) gross weight with CAST 2 accessories 25 kg
Factory test certificates (included)	SMPS size distributions, factory calibration MD19-1iC dilution ratio, factory calibration

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Calibration (included)	Coulometric carbon (EC and OC) analysis of test aerosol by SUVA (Schweizerische Unfallversicherungs-Anstalt, Luzern)
Calibration (optional) (only for version with diluter MD19-1iC)	Calibration of diluted test aerosol in number concentration and particle mobility size by METAS (Metrology and Accreditation Switzerland, Bern)
Service (optional)	Starting up on customer site with instructions in CAST operation

Ordering Instructions

Type (possible options)	MD19-1iC Diluter (D)	LabView PC Software (C)	Absolute pressure control with MD19 (A)	Back pressure compensation (P)	Remarks
CAST 2	no	No	no	no	Later extensions to versions –D and –C are possible without sending back the CAST 2 system
CAST 2-D	yes	no	no	no	
CAST 2-C	no	yes	no	no	
CAST 2-DC	yes	yes	no	no	
CAST 2-DCA	yes	yes	yes	no	
CAST 2-P	no	no	no	yes	
CAST 2-CP	no	yes	no	yes	
CAST 2-DCP	yes	yes	no	yes	
CAST 2-DCAP	yes	yes	no	yes	

Requirements for CAST 2 operation

Laboratory environment with efficient air ventilation and with installation for suction of exhaust and combustible gases from the burner

oil free and dried (< 10 % r.h. at 23 °C) compressed air with flame protection- and pressure reducing valve adjustable from 4 bar to 6 bar (rated pressure 5 bar).
6 mm Swagelok connection for CAST gas tube
gas consumption 35 – 65 l/min

N_2 gas in compressed air bottle with pressure reducing valve adjustable from 4 bar to 6 bar (rated pressure 5 bar)
Purity 99.999 %, recommended size 50 l.
6 mm Swagelok connection for CAST gas tube
gas consumption appr. 10 l/min

C_3H8 gas in compressed air bottle with flame protection and pressure reducing valve adjusted on 1.6 - 2 bar.
purity 99.95 %, recommended size 1 l.
6 mm Swagelok connection for CAST gas tube
gas consumption appr. 0.1 l/min

Specification may change without notice