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Developments for the Removal of Slag Droplets from Flue Gas Streams Following Slagging Combustion of Hard Coal

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1 Introduction

The development of combined cycle power processes is an attractive option to raise the efficiency of electric power generation based on fossile fuels.

Natural gas fired gas turbines followed by a conventional steam generator are commercially well established. For utilisation of alternative fuels in combined cycle technologies gasification or pressurised combustion followed by gas cleaning converts a solid fuel into a suitable gas turbine feed.

The pressurised pulverised coal combustion under high temperature "slagging" conditions offers the most economical potential for combining availability and low fuel prices of coal with the high efficiency of combined cycle technology. However the flue gas has to be effectively cleaned from slag prior to use in gas turbines. Modern turbines require slag droplet concentrations of as low as 3 – 5 mg/m_n^3 and a droplet size lower than 3 – 5 µm. Given the severe operating conditions (p > 10 bar, ϑ > 1400 °C, volume flow > 10^6 m_n^3/h) separation by inertial forces is regarded as the most feasible available option. Only few - at the given operating conditions unreliable design procedures - for adapted separators are available. Based on cold flow modelling this paper describes experimental results of three types of separators; particular characteristics relevant for optimisation of a large scale design can be identified.

2 Fixed bed granular filter

2.1 Cold flow experiments

For the design of granular bed filters a well known model by Suekane (1) predicts fractional and overall separation efficiencies (table 1).

Table 1: Theory according Suekane

$St = \frac{\rho_G w d_p^{\ 2}}{9\mu d_K}$ (Stokes number)

$Re = \frac{\rho_G w d_k}{\mu}$ (Reynolds number)

$St_{eff} = f(St, Re, \varepsilon)$ (correlation according to experimental data)

$T_s(x) = \frac{St_{eff}^{2\ 3}}{40 + St_{eff}^{2\ 3}}$ (fractional separation efficiency of a single sphere)

$T_{Bed}(x) = 1 - exp\left(-1{,}5\frac{(1-\varepsilon)}{\varepsilon}\frac{L}{d_k}T_s(x)\right)$ (fractional separation efficiency of the bed)

Definitions:

Fractional separation efficiency: $T(x) = E.\frac{q_{out}(x)}{q_{in}(x)}$

Total separation efficiency: $E = 1 - \frac{c_{out}}{c_{in}}$

In order to test the applicability of the Suekane model a cold flow model with a scale factor 1/10 was built and operated. (Fig. 1) According to the Suekane model the characteristic dimensionless numbers for the system /flue gas – slag/ at operating conditions is similar to /air – silicon oil/ under atmospheric conditions; hence this system is regarded as suitable for cold flow modelling. The collection efficiency of a fixed bed granular filter generally increases with decreasing size of bed particles; however with respect to the drainage of the slag as well as to the design of the bed support the diameter of the particles have to be > app. 20 – 30 mm. This particle size has been chosen for the tests.

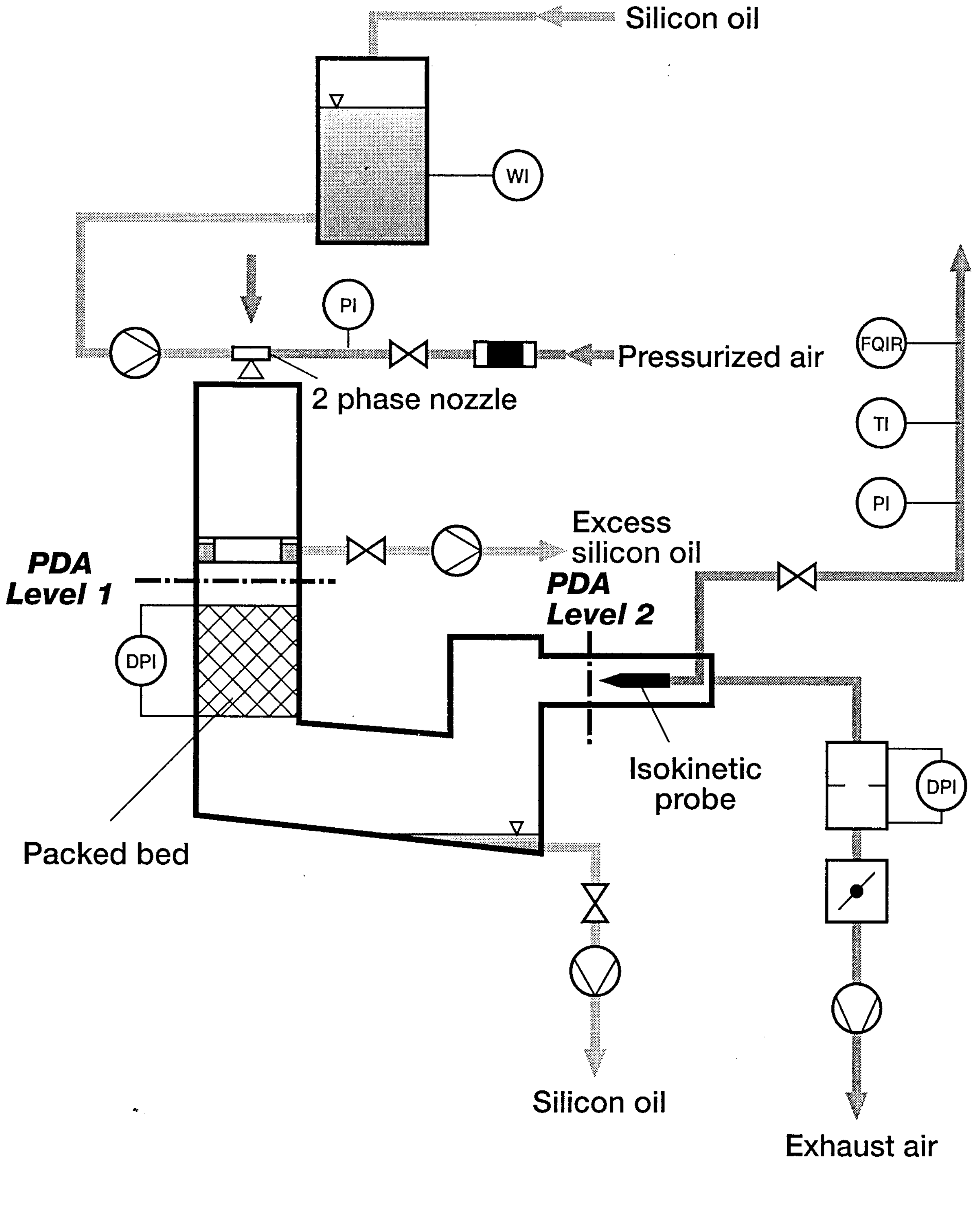

Fig. 1: Packed bed separator - Test device

Table 2 presents the range of operating conditions for cold flow tests as well as the model parameter as related to a commercial sized plant.

Table 2: Range of operating conditions for model-testing of a packed bed separator

Bed height	H $= 220 - 660$ mm
Diameter of bed particles	$d_k = 12 - 30$ mm
Free board velocity	$w_o = 2 - 3$ m/s
Liquid concentration at inlet	$2 - 20$ cm^3/Nm^3
(Slag concentration at separator inlet in a industrial plant	$2 - 4$ cm^3/Nm^3)

<u>Comparison of the dimensionless numbers, related to the separation process</u>

	Industrial plant (flue gas/slag)	Model (air/silicon oil)
	$\rho_G = 2{,}5$ kg/m^3	$\rho_G = 1{,}19$ kg/m^3
	$d_p = 5 \mu m$	$d_p = 5 \mu m$
	$w_0 = 4$ m/s	$w_0 = 3$ m/s
	$d_K = 40$ mm	$d_K = 30$ mm
	$\mu = 5{,}81 \cdot 10^{-5}$ kg/m.s	$\mu = 1{,}86 \cdot 10^{-5}$ kg/m.s
$Re = \frac{w_0 d_k p_G}{\mu}$	6879	5758
$St = \frac{\rho \ w_0 d^{\ 2}}{\mu d_k}$	$1{,}0749 \cdot 10^{-4}$	$1{,}599 \cdot 10^{-4}$
St_{eff} [-]	$1{,}14 \cdot 10^{-2}$	$1{,}58 \cdot 10^{-2}$

Air and silicon oil are fed cocurrently through a two phase nozzle onto a granular bed. Filter particles are ceramic balls with similar surface properties as

envisioned for a high temperature separator. The oil film which forms at the wall of the first vertical shaft as a result of the nozzle spray angle, is removed through an annular trough.
Droplet size distribution before and after the filter bed was measured by PDA (phase Doppler anemometer) method, total droplet concentration downstream of the separator was measured by the weight increase of an isokinetic filter probe.

2.2 Results

As expected, the overall separation efficiency increases with gas free board velocity. Fig. 2 shows a typical result for droplet loadings comparable to flue gas cleaning downstream of a slagging combustor.

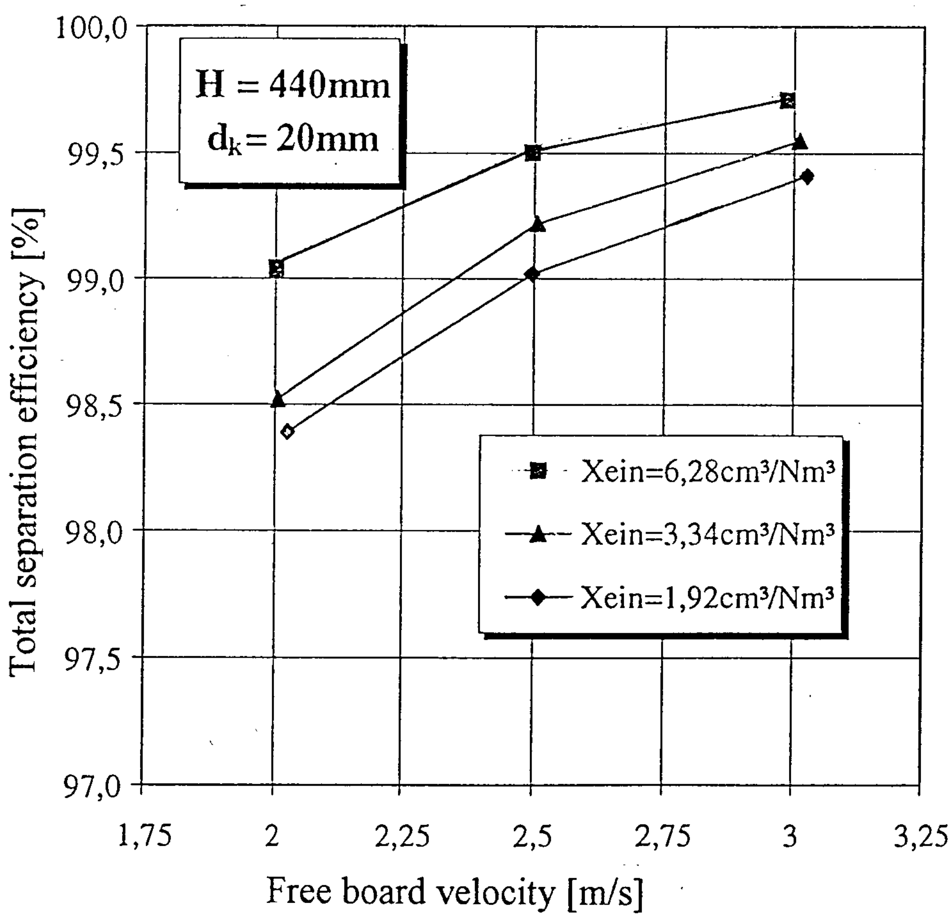

Fig. 2: Packed bed separator – Total separation efficiency as function of free board velocity

Under normal combustor operating conditions separation efficiencies above

99 % are required.

The separation efficiency decreases sharply below 4 – 6 μm for almost all test conditions. This is reflected in the size distribution in the clean gas (Fig. 3).

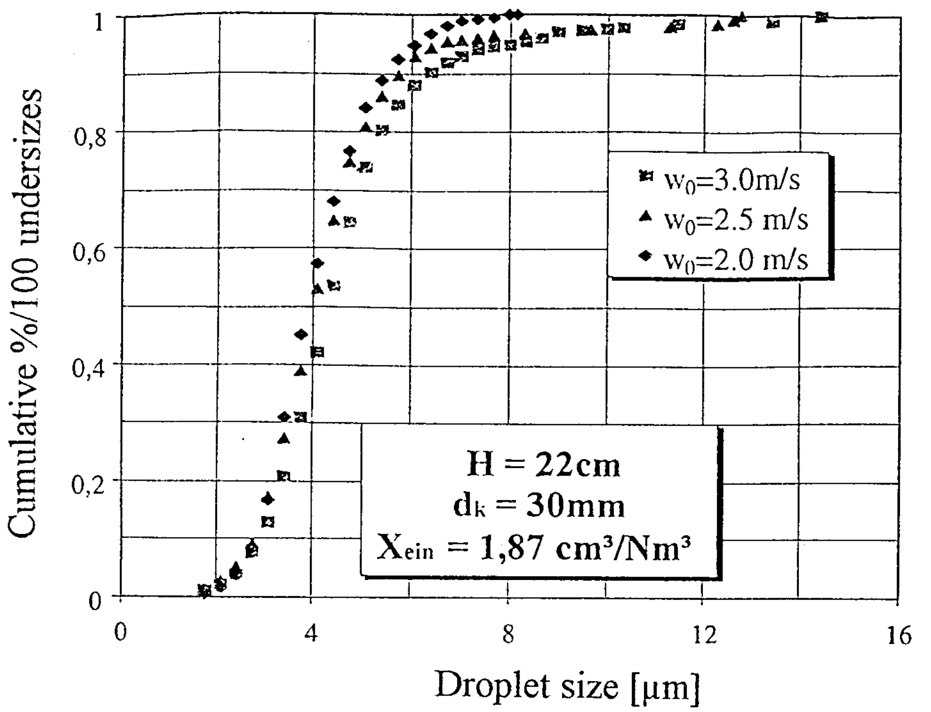

Fig. 3: Packed bed separator – Cumulative size distribution (clean gas)

It should be noted that the PDA-measurement has limitations below 2 – 3 μm, hence the size range below 2 μm could not be accurately investigated. Fractional separation efficiencies as compared to the Suekane model are given in fig. 4. The Suekane model generally follows the experimental data except below app. 3 μm where PDA measurement becomes inaccurate. For all test conditions the model predicts slightly better separation efficiencies than measured.

2.3 Wire mesh separation

Wire mesh separation is a common and effective device for droplet removal e.g. downstream of a gas-liquid contact apparatus (washing columns, absorption etc)

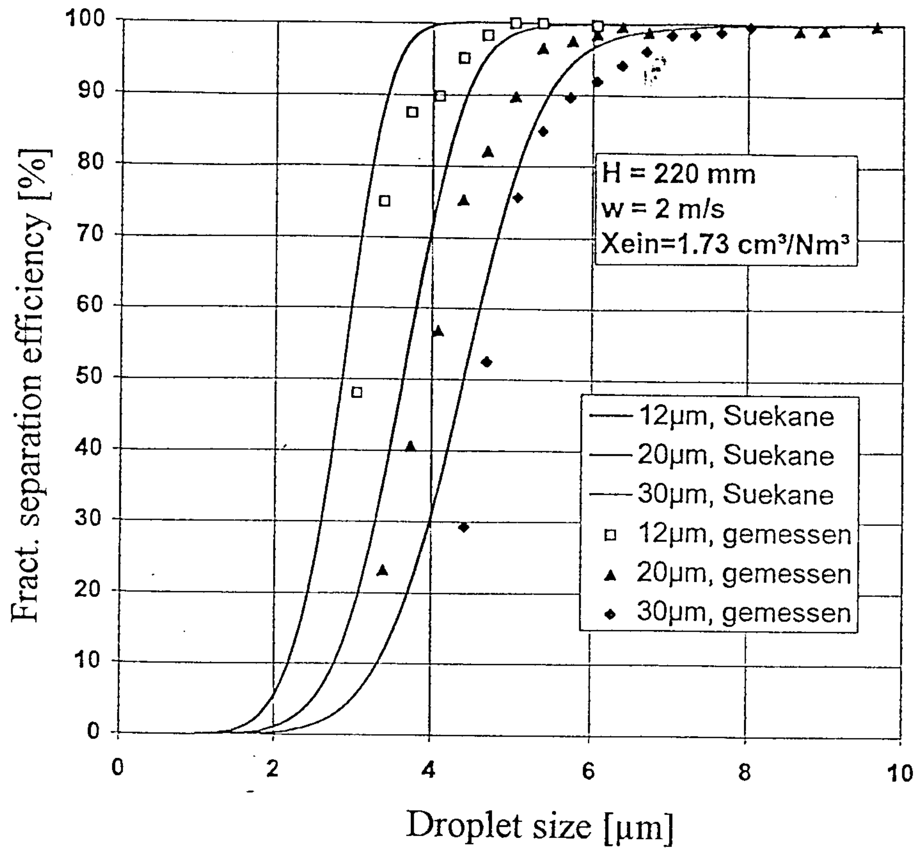

Fig. 4: Packed bed separator – Fractional separation efficiency as function of diameter of the spheres and the droplet size

In spite of the widespread use reliable design procedures based on hydrodynamic principles are rare. The application in slag removal is however only a remote possibility, material constrains will prevent the use in the foreseeable future; however for reasons of comparison a wire mesh element has been tested downstream of a granular filter.

Wire mesh separation in upflow operation (countercurrent film and gas velocity) limits the freeboard gas velocity; high velocities will increase the hold up of the collected liquid and may result in an unstable operation. Hence the operating conditions for wire mesh tests are not fully comparable to the tests described earlier. For the tests the same experimental facilities were used as before.

Fig. 5 presents typical results for the fractional separation efficiencies of a typical commercially available stainless steel wire mesh. It is evident, that below 2 – 3 µm the efficiency of this separator type drops significantly. It is assumed that even at moderate freeboard velocities some entrainment of small droplets

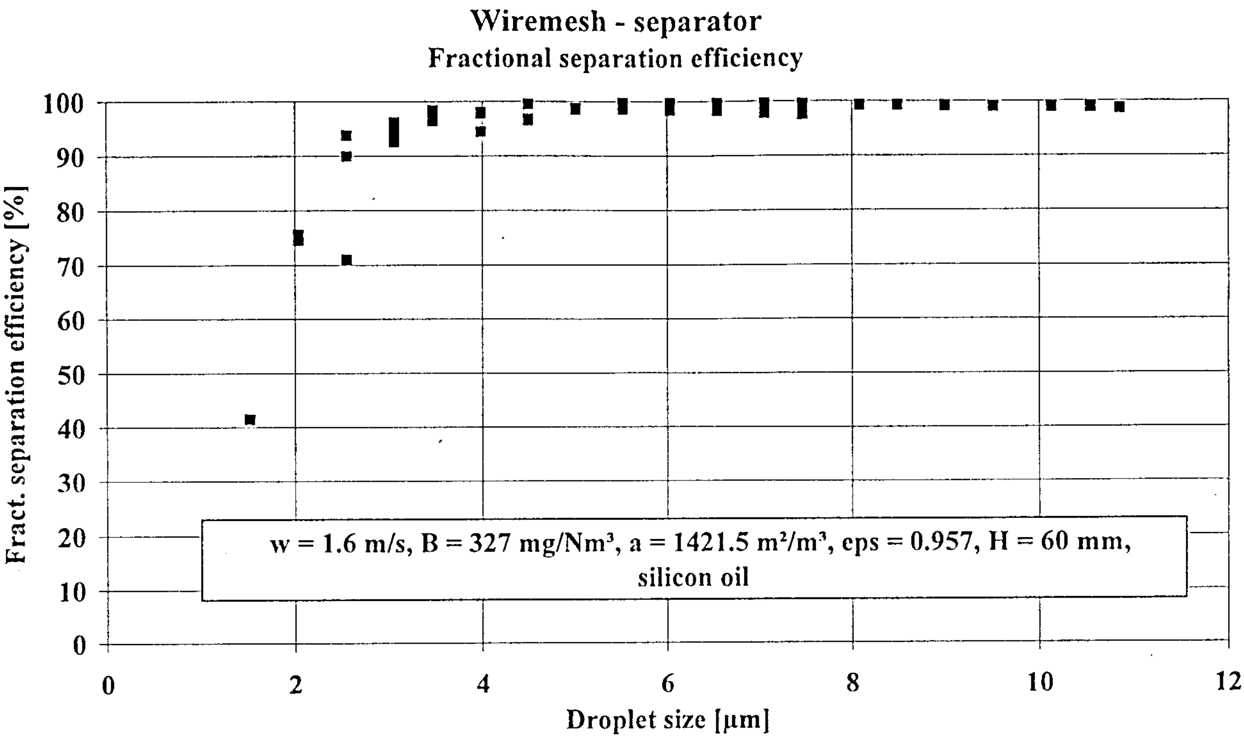

Fig.5: Fractional separation efficiency of a wiremesh - separator

occurs. Increasing gas velocity will improve the collection efficiency; as indicated above, hold up limitations will limit the range of free board velocities. For the moment wire mesh separation is not regarded as a technical and economical option for the problem of slag separation.

3 The Multiwir separator

The Multiwir separator (2) is formed by a structured packing with a mulitude of vortices; main area of application is the demister after steam generation and the elimination of very fine droplets downstream of distillation or absorption columns. Although significant material and design problems are still be to solved for high temperature applications, the available experience indicates an attractive potential especially for the separation of droplets below 3 µm.
The commercially available Multiwir separator is a multichannel thin plate structure which is optimised with regard to the development of stable vortices. High temperature applications will require an increased wall thickness if

ceramic materials are used; this could affect the development of vortices and hence the separation efficiency.

Preliminary flow tests on a model separator (fig. 6) indicated that vortices develop even for the unfavourable ratio of wall thickness and channel width.

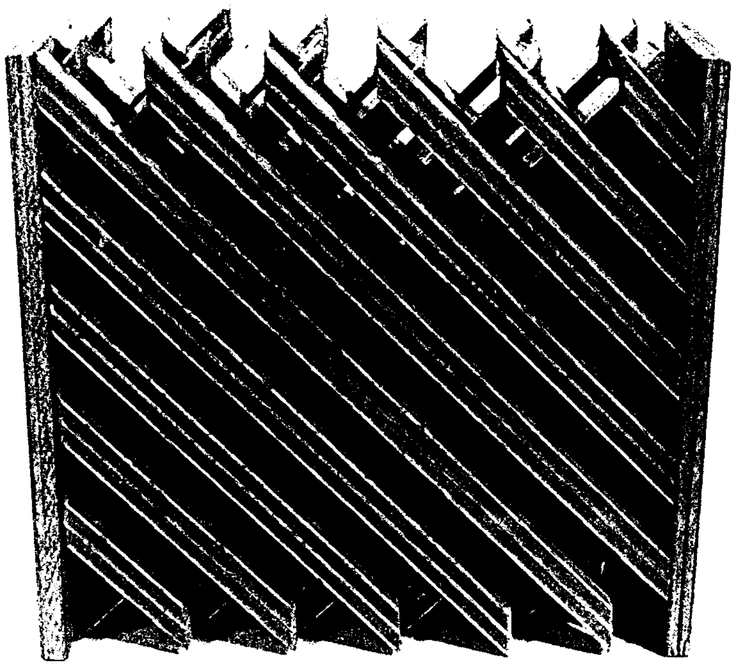

Fig. 6: Model of one Multiwir element

Similar to the cold flow test on fixed bed separation a cold flow Multiwir model was set up and tested (Fig. 7). The cross-section of the separator duct was 163 x 190 mm; up to 3 Multiwir elements of L = 300 mm each could be tested. Prior to the separator coarse droplets are separated by a packed bed in order to improve the accuracy of the separation measurements. The separated oil is collected in the duct downstream of the Multiwir; in order to remove reentrained droplets a further packed bed is installed downstream. For practical reasons droplet size upstream and downstream of the Multiwir is now analysed by a cascade impactor; the impactor will extend the size range to below 2 – 3 µm, although at reduced accuracy.

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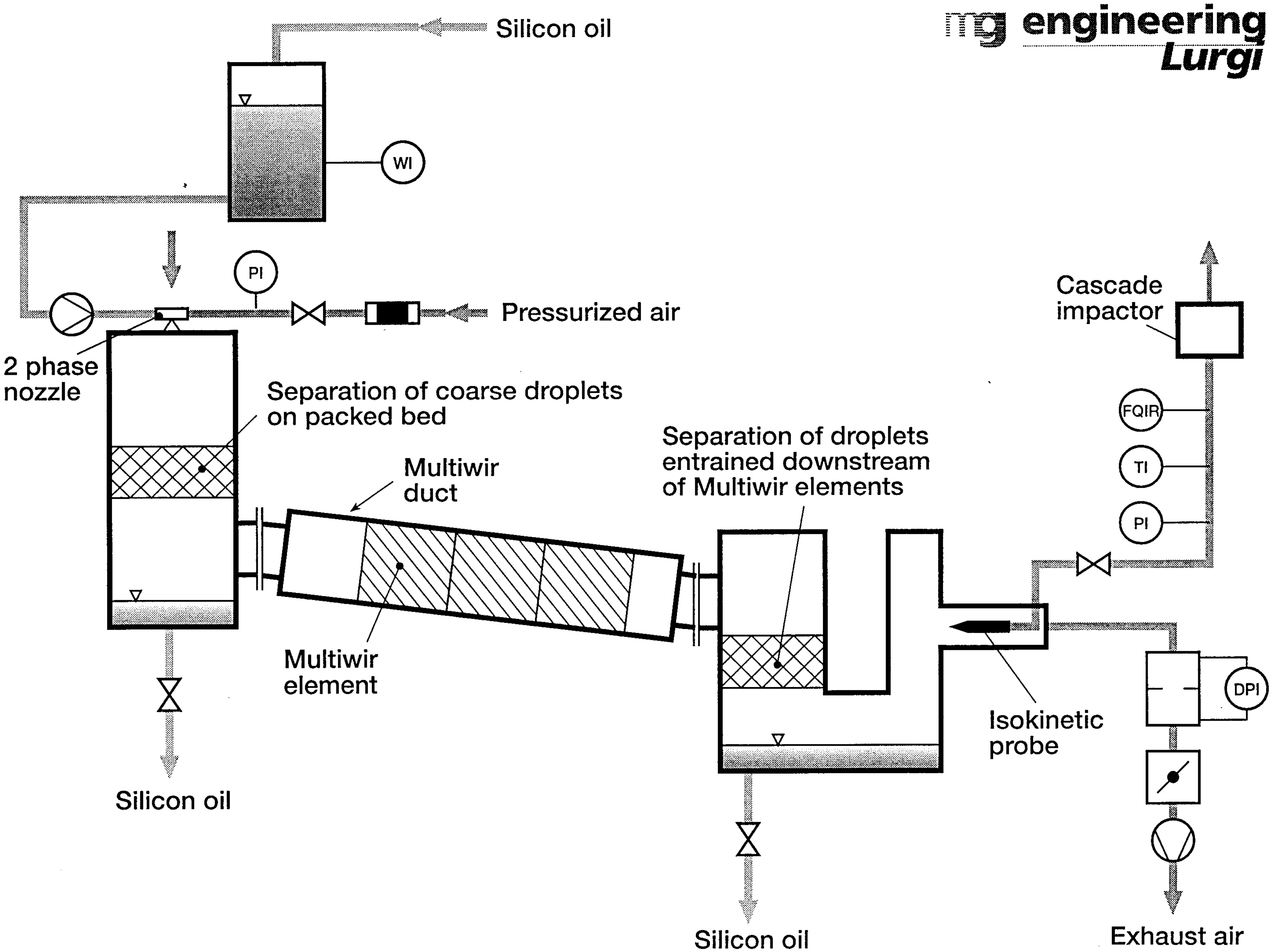

Fig. 7: MULTIWIR - Test device

Because of the different measuring principles direct comparison of size distributions may be inacurate whereas for collection efficiencies (analysis of inlet and outlet conditions) the potential error will decrease. Fig. 8 presents fractional collection efficiencies for several arrangements of the Multiwir separator.

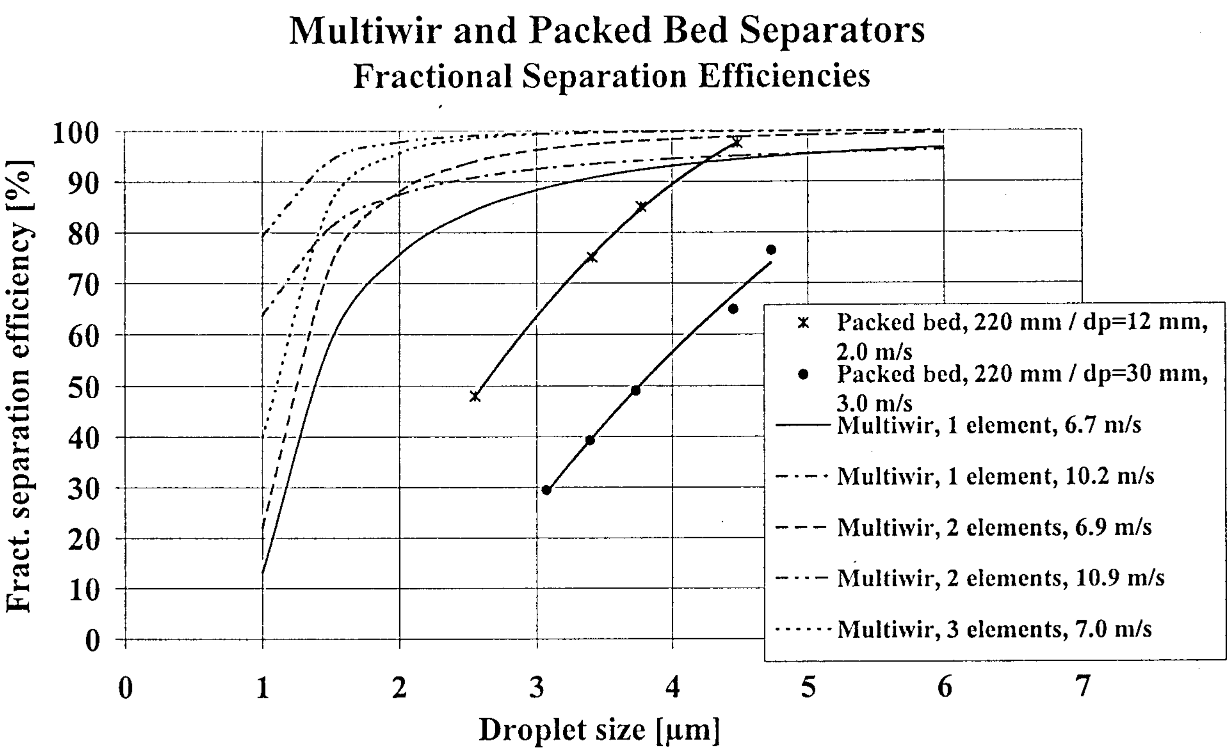

Fig. 8: Fractional separation efficiency of tested Multiwir- and packed bed - separators

As indicated, the performance of a Multiwir separator compares favorably with packed beds especially at low droplet sizes.

Multiwir separators are generally operated at higher free board velocities than packed beds. The higher velocities result in higher pressure losses as given in table 3.

Table 3: Multiwir and Packed Bed Separators. Comparison of the pressure drop and the fractional collection efficiency for droplets ∅ 2.5 μm

	w_0 [m/s] *)	$\eta_{2.5\,\mu m}$ [%]	Δp [mbar]
Multiwir, 2 elements, L = 600 mm	6.9	93.6	31.0
Multiwir, 3 elements, L = 900 mm	7.0	98.3	44.6
Packed bed, H=220 mm, d_p = 12 mm	2.0	45.0	16.8
Packed bed, H=220 mm, d_p = 30 mm	3.0	10.0	11.6

*) Free board velocity in the gas duct

Although the collection efficiency of Multiwir is very much higher than the comparable packed bed, the pressure loss is still kept within acceptable limits.

4. Conclusions

The nearly complete removal of slag droplets prior to the turbine is indispensable for establishing IGCC technology based on pulverised coal combustion at high pressures and temperatures. Cold flow modelling shows the collection efficiency of packed granular beds to be significantly lower than comparable Multiwir separators. The model data indicate that an adapted Multiwir separator can be capable to meet the limits set by turbine operation. Under high temperatures and pressures a Multiwir separator must be constructed from ceramic materials. In spite of the adverse shape caused by material constraints the performance under cold flow conditions is superior to a packed bed of a realistic bed particle size range (20 – 30 mm). Further research is required to understand the hydrodynamics in Multiwir channels in order to optimise shape and operating conditions and to set dimensions for a plant of industrial size.

List of Symbols

(if not explained in text)

c_{in}	- Liquid concentration at inlet
c_{out}	- Liquid concentration at outlet
d_k	- Diameter of particle (packed bed)
d_p	- Droplet diameter
L	- Lenght of one Multiwir element
$q_{in}(x)$	- Mass fraction of particles of the size x at inlet
$q_{out}(x)$	- Mass fraction of particles of the size x at outlet
w_0	- Free board velocity of gas
x_{ein}	- Liquid concentration at inlet
ε	- Void fraction (packed bed, wire-mesh)
μ	- Viscosity of gas
ρ_G	- Density of gas

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List of Keywords

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Combined Process
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Separation Efficiency