ELECTROSTATIC PRECIPITATOR PENETRATION FUNCTION FOR PULVERISED COAL COMBUSTION AEROSOLS

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Abstract

The penetration of fly ash particles through the electrostatic precipitator (ESP) was determined as a function of particle diameter in the size range of 0.02-0.7 µm at a 300 MW boiler. Differential mobility analyser (DMA) and condensation nucleus counter (CNC) were utilised to simultaneously determine number size distributions before and after the ESP. In addition, total mass penetration was determined with traditional filter sampling method and gas composition (O_2, CO_2, CO, NO_x and SO_2) with gas analysers. Measured mobility distributions were inverted to the desired number size distributions by a commercial algorithm and by an advanced constrained regularization algorithm. Fractional penetration functions were calculated as the ratio of number size distributions determined after and before the ESP, respectively. Total mass penetration was measured to be about 0.3 %. Penetration functions showed a bimodal structure. Penetration increased from less than 2 % to 17 % when increasing particle size from 0.05 µm to 0.15 µm, decreasing to 5 % at 0.2 µm particle diameter, further increasing to about 12 % at 0.4 µm particle diameter and finally decreasing below 2 % at about 0.7 µm particle diameter. During the measurements, the currents in ESP sections 1 and 2 were 500 mA and 600 mA, and voltages 57 kV and 55 kV, respectively. The current and voltage of third section were 170 mA and 43 kV. This might be one reason for the observed bimodality of the penetration function.

Introduction

In the coal fired power plants with capacity of hundreds of megawatts, commonly used device to reduce particle emissions is the electrostatic precipitator (ESP). Within the ESP the electric field has direct influence to the fly ash particles and the units can handle large amounts of gases without significant pressure drops. Dry fly ash is collected, mechanically the ESPs are simple and therefore rather easy to maintain. The particle collection efficiency of 99 % based on total mass can be achieved. However, in sub micrometer range 0.1-1.0 µm penetration can be tens of percents (1,2).

Sub micrometer particles are formed during the condensation of vaporised ash matrix components (3,4). They are enriched with the toxic trace species like Pb, Cd, V and As (5-7). Fine particles have long residence times in the atmosphere and have access deep into human respiratory system. On their surfaces fine particles carry toxic, highly soluble ash species into alveolars and blood circulation of human beings (8).

Recent concern about the adverse environmental effects of coal combustion trace metal emissions is likely to reduce the particulate emission limits for coal fired boilers. Also emission limits for trace metals have been considered. Therefore, ESP collection efficiency needs to be increased, especially for the sub micron combustion aerosol particles. We have studied the electrical agglomeration method to increase the ESP efficiency (9). As a part of this study, we have determined the ESP penetration function for pulverised coal fired boiler fly ash, which we need to know in detail in order to estimate the ESP efficiency increase due to electrical agglomeration.

Experimental

Boiler Description

The boiler had the fuel rated capacity of 315 MW. During the measurement period pulverised bituminous Polish coal was fired into the furnace producing 2/3 of the maximum power. The concentrations of NO_x, SO_2, CO_2, CO, and O_2 were monitored by gas analysers located after the ESP. Particle mass concentrations before and after the ESP were measured with the isokinetic filter sampling probe. Flue gas water content was determined by the volume of water condensed from the gas sampled through the filter. Gas composition and particle mass concentration data is given in Table 1. Bituminous coal had 0.65 % sulphur and 9.6 % ash. Load of the boiler was 208 MW based on the input coal heat value.

Table 1. Process parameters during experiments. Flue gas temperature 415 K±4 K.

SO_2, [ppm]	415
NO_x, [ppm]	250
O_2, [%]	6.7
CO, [ppm]	32
CO_2, [%]	12
H_2O [kg/kg], (dry gas)	0.042
Particle mass concentration after ESP, [g/Nm^3]	0.054
Particle mass concentration before ESP, [g/Nm^3]	12

ESP Description

The ESP was a three section unit having wire-plate-geometry. The effective separation area of the collection plates was 11 000 m^2, which was divided into three sections. In each section effective height was 13.5 m, width 10.8 m and length 3.75 m. Total volumetric gas flow was 120 m^3/s with the average velocity of 1.23 m/s. The plate to plate distance was 30 cm. Each section had 1620 emission rods with the diameter of 2.7 mm. The design maximum voltage was 70 kV and current 1600 mA. Nominal current per separation plate area was 0.44 mA/m^2. The ESP operating voltage and current were recorded from each block during measurements, and the results for the particle size distribution measurement periods are presented in the Table 2.

Table 2. ESP operating conditions. Total gas flow was 120 m^3/s, total effective separation area 11 000 m^2 and the flue gas temperature 415 K±4 K.

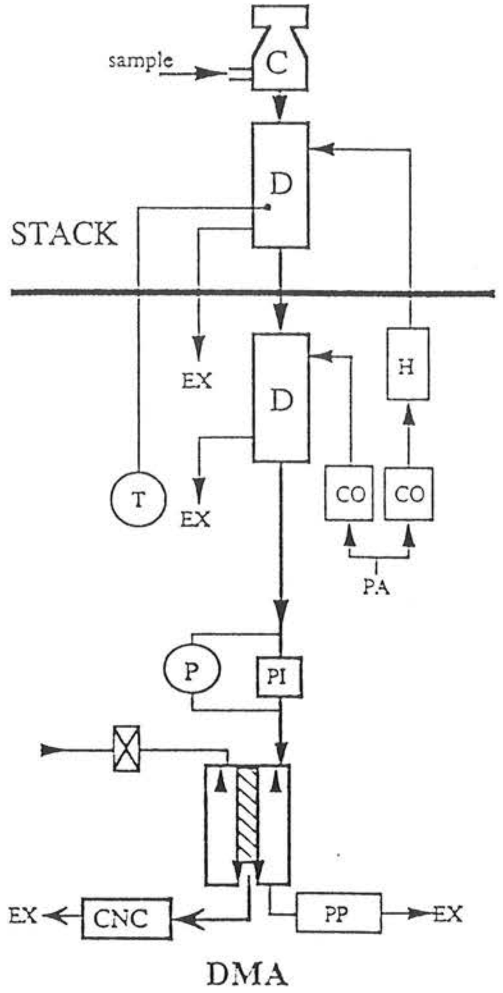
DMA-Sample Nro	Block 1.		Block 2.		Block 3.	
	Current [mA]	Voltage [kV]	Current [mA]	Voltage [kV]	Current [mA]	Voltage [kV]
1	540	57	597	55	170	43
2	513	56	600	54	173	43
3	407	56	533	54	173	43
4	620	58	613	55	153	42
5	513	58	660	55	167	44
6	493	58	660	55	167	44
7	440	56	607	55	187	43
8	440	56	607	55	187	43

Aerosol Size Distribution Measurements

In Figure 1 we show combustion aerosol number size distribution measurement system. Aerosol was sampled in the stack through a pre-cyclone having the Stokes cut diameter of 2.5 µm. The aerosol sample was diluted in a two stage, ejector based dilution system (10). First dilution occurred at stack conditions by clean, dry air heated to the stack temperature to reduce partial pressure of condensable species and accordingly to eliminate new particle formation by homogenous nucleation of sulphuric and hydrochloric acids and water. Second dilution was carried out by ambient temperature clean dry air.

The number size distribution of the diluted aerosol was measured with the differential mobility analyser (DMA, 11) by using the condensation nucleus counter (CNC) as a number concentration sensor.

Before the experiments, comparison between the simultaneously operated electrical mobility analyser apparatus, to be situated before and after ESP, was carried out in the laboratory conditions. During the laboratory measurements sampling flows of the mobility analysers and readings of the two CNCs were conformed to be equal, respectively.



⊠	Absolute filter
C	Cyclone
CNC	Condensation nucleus counter
CO	Critical orifice
D	Diluter
DMA	Differential mobility analyzer
EX	Excess
H	Heater
P	Pressure gauge
PA	Pressurized air
PI	Pre-impactor
PP	Pump
T	Temperature measurement

Figure 1. Combustion aerosol number size distribution measurement system.

Data Inversion

ESP penetration function $P(D_p)$, number concentration data y_i measured for each DMA voltage, measurement error Δy_i, size distribution function $f(D_p)$, and DMA kernel function $k_i(D_p)$ corresponding to each DMA voltage are related through the Friedholm integral equations written separately for each DMA channel,

(1) $$y_{i,b} \pm \Delta y_{i,b} = \int k_i\left(D_p\right) f_b\left(D_p\right) dD_p$$

(2) $$\begin{aligned} y_{i,a} \pm \Delta y_{i,a} &= \int k_i\left(D_p\right) f_a\left(D_p\right) dD_p \\ &= \int k_i\left(D_p\right) P\left(D_p\right) f_b\left(D_p\right) dD_p \end{aligned}$$

Here b and a denote to the conditions before and after ESP, respectively. Methods used to determine size distribution functions f_b and f_a included the constrained regularization algorithm (MICRON, 12) and the software delivered by the manufacture of the DMA (13). In the inversions, particle losses in DMA and sampling lines, CNC-counting efficiency, charge distribution and pre-impactor collection efficiency were taken into account (12). The ESP penetration function was calculated from

(3) $$P\left(D_p\right) = \frac{f_a\left(D_p\right)}{f_b\left(D_p\right)}$$

Results and Discussion

The size distributions as inverted by TSI and MICRON algorithms are shown in Figures 2 and 3, respectively. In the Figure 4 the experimental penetration curves are compared.

Sub micron number size distributions before and after the ESP are bimodal. The modes are at 0.05 µm and 0.30 µm before the ESP and at 0.078 µm and 0.37 µm after the ESP as determined from size distribution inverted with the TSI algorithm. The size distributions determined by the TSI algorithm agree moderately well with those determined by the regularization algorithm. Also the penetration function (Figure 4) show bimodal shape with peak penetration values of 12 % at 0.15 µm and 0.40 µm as determined from the size distributions derived with TSI algorithm.

The bimodal shape of the determined penetration function differs significantly from that proposed by ESP theory and also from those determined in earlier studies (1,2). In earlier studies, however, aerosol size distributions were measured with the instruments having significantly lower size resolution and

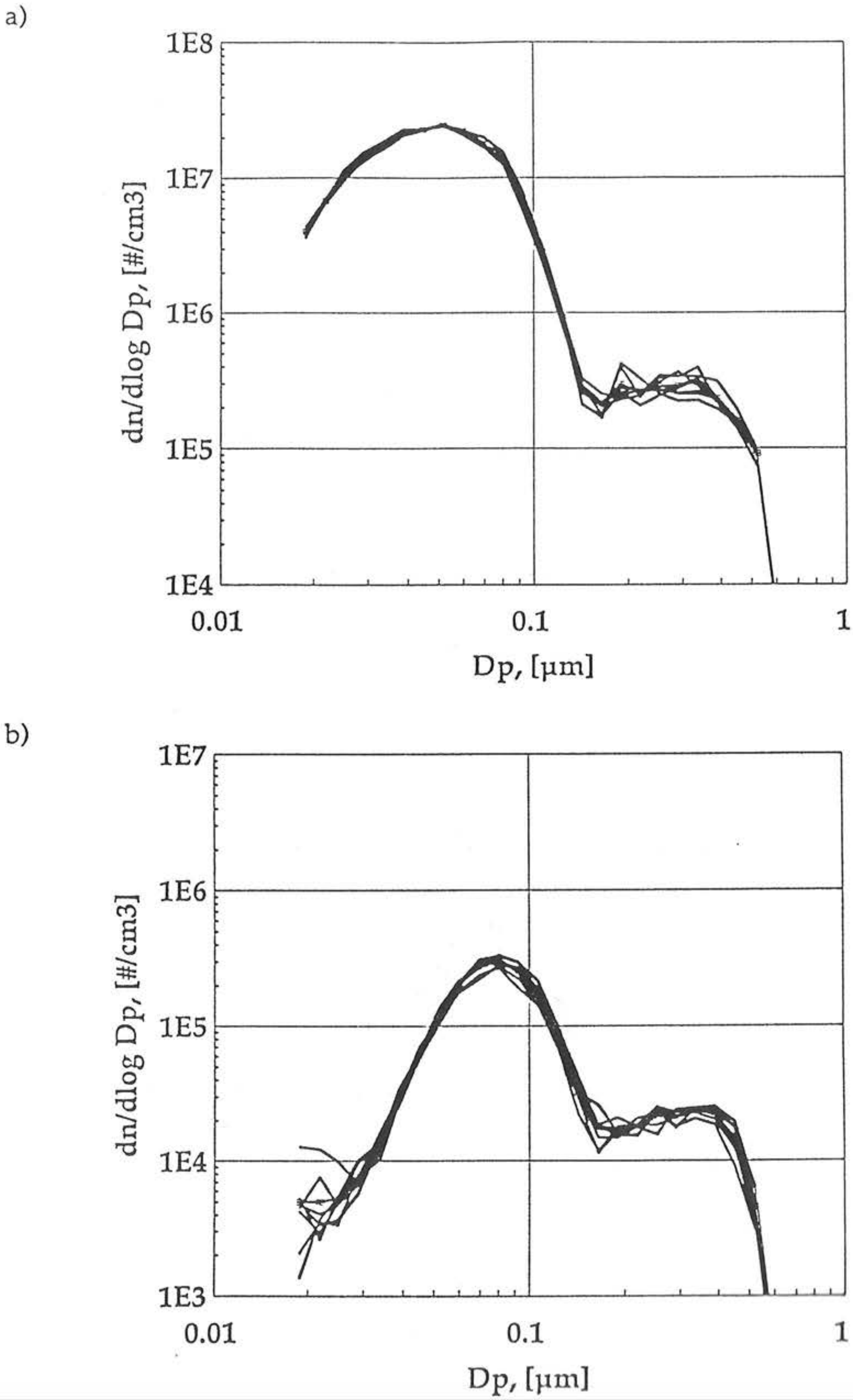


Figure 2. Number size distribution functions a) before and b) after the ESP as inverted with the commercial inversion algorithm (13).

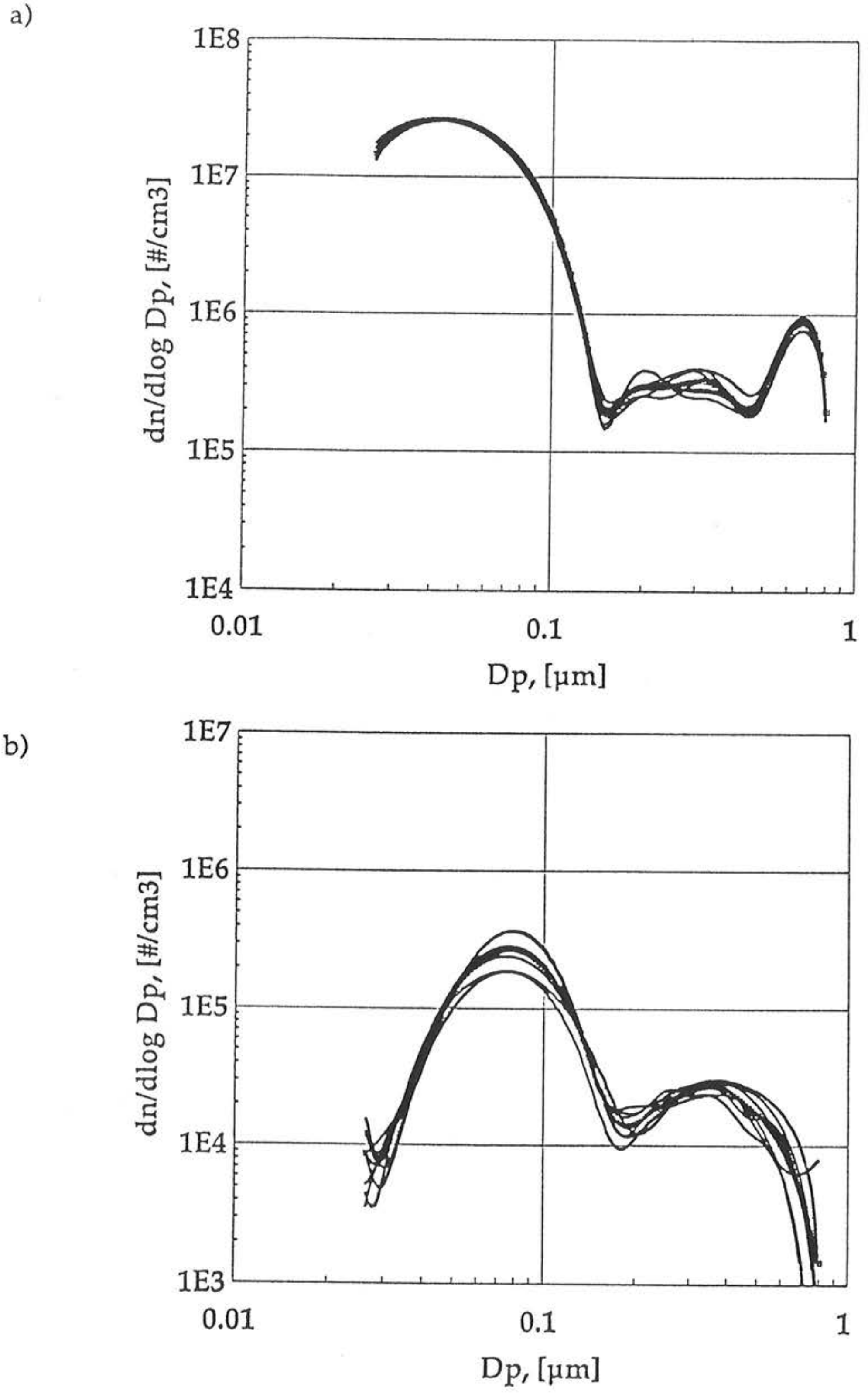


Figure 3. Number size distributions a) before and b) after the ESP as inverted with the method based on constrained regularisation (12).

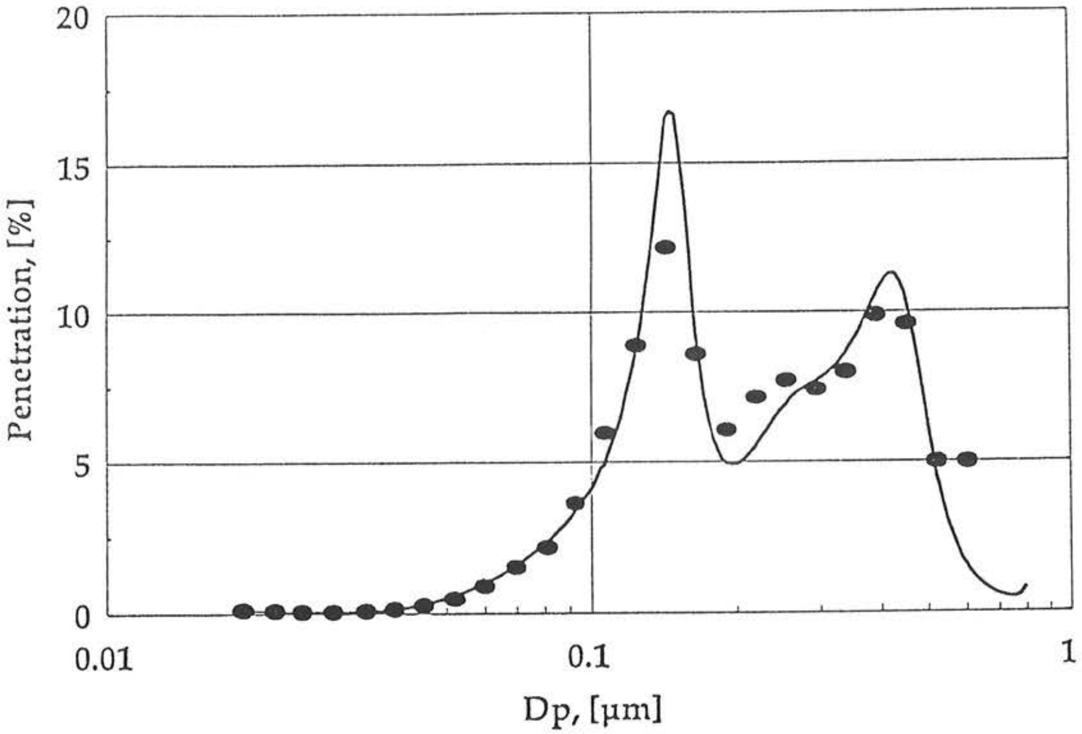


Figure 4. Experimentally determined aerosol penetration functions for ESP determined as an average of individual penetrations calculated from the samples 1-8 after and before the ESP, respectively. Solid line indicates the result from size distributions inverted with the method based on constrained regularization. Circles indicate result based on distributions derived from TSI algorithm.

the problem of detailed data inversion was not discussed. The reason for the bimodality is not yet clear. When we consider the ESP operating parameters (Table 2), we realise, that the currents and voltages of the ESP section 3 were significantly lower as compared to those of sections 1 and 2. This may cause the observed bimodality of the penetration function.

Definitely more studies are needed to explain the bimodal shape of the ESP fractional penetration. The penetration window seems to be quite narrow with respect to particle size. Therefore, in the size range of 0.08 - 0.8 µm, particle concentration reduction due to e.q. electrical agglomeration will significantly increase the ESP collection efficiency for the sub micrometer fly ash particles. Also, the environmental effects depend on the characteristics of the particles in both sub micron modes. Therefore, the detailed mechanisms for the formation of these modes need to be clarified.

Summary

Number size distribution of the pulverised coal combustion fly ash has two sub micrometer modes at 0.05 µm and 0.3 µm, respectively, when measured before the ESP. Also ESP penetration function show two penetration modes at about 0.15 µm and 0.4 µm. The total mass penetration was 0.3 %. The maximum penetration was measured to be as high as 17 %.

Acknowledgements

The Ministry of Trade and Industry of Finland has been supporting this research via SIHTI environmental engineering research program. IVO and Tampella Power are also gratefully acknowledged for their financial support. The staff of IVO stack testing group for carring out gas comparison and total particle mass measurements as well as boiler operating staff for their help during experiments are acknowledged.

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