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THE DISCHARGE OF FILTER CAKE BY AIR BLOW BACK; A MATHEMATICAL SIMULATION TO IMPROVE DESIGN AND OPERATION OF DISC FILTERS

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ABSTRACT

The filter cake is discharged from the segments of rotary vacuum dis filters, usually by means of compressed air blow back. In order to operate the disc filter with high speed of rotation or to ischarge an adhesive filter cake, it is necessary to optimize the design of the discharge equipment and the operating conditions.

Proceeding from equations describing the throughput of compressed air through the pipeline system of the disc filter, the pressure in the filter segment and the motion of the filter medium, the acceleration of the filter cake is calculated by a mathematical simulation. The influence of the design of the filter segment, the control head and the pipe diameter on the acceleration of the filter cake is discussed and possibilities to improve existing equipment of disc filters are shown.

Fig. 1 shows the operating principle of sc filter. It consists of a vertical-y arranged disc that turns about its axis of rotation, dipping with 40-50% into a suspension. The disc consists of individual filter cells in the shape of circular segments which are covered by a filter cloth.

During the rotational motion, the individual filter cells censecutively dip into the suspension. The filter cells are evacuated via a control mechanism. As a result of the vacuum in the filter cell, the suspension liquid flows through the filter cloth into the filter cell and from there through a piping system into a filtrate separator. A solid material is deposited on the filter cloth by a cake-forming filtration process and is carried out of the suspension together with the filter cell.

The cell emerges from the suspension during the further course of the rotational motion. Air from the environment of the filter cell is aspirated into it, thereby removing moisture from the filter cake.

This is followed by the removal of the filter cake from the filter cloth. For this purpose, compressed air is usually forced into the filter cell which tensions the filter cloth and the filter cake. When the filter cloth is taut, the cake dislodges and slides over a scraper into a solids chute. Cake and filtrate are disposed off separately.

Today, almost all filters operate with a plane control head (Fig. 1). In addition to the filter incorporating shafts with up to 12 filter discs filter with individual troughs and discs have been developed. The number of filter segments on a disc has been increased up to 30 and the thickness reduced. The typical rotational speeds of the filters are now much higher than before. Drive modules, which can be exchanged as compact units, are commonly used. For further information regarding the development and present standard of this filter technique, see [1,2,4,5, 6,12,14, and 17].

The inexpensive design of the disc filter and its very large filter area in relation to its size have resulted in a wide field of application for the removal of solids from liquids, particularly in industries involved in the processing of coal, ferrous and non-ferrous metals [8,14,15].

This broad range of application of the disc filter is characterized by the fact that large mass flows of products with a low specific price/mass flow ratio can be processed. Thus, in order to be cost-effective, disc filter must attain high specific solids/filtrate throughputs [5,7,9,10,11,23,35]. Further developments of the disc filter to permit higher rotary speed and therefore to lower specific costs are essential.

of the filter-cell, in equilibrium with the elastic tensile stress of the filter cloth, which will be explained later.

An improvement of the cake discharge can be accomplished by means of constructive improvements to the inlet-valve geometry. An example of this is the rectangular valve, the area of which being plotted as curve 1, in Fig. 2, where the gradient can be observed to be significantly steeper. In order to improve older filters, constructed with a circular pipe overlap, the control zones can be subsequently modified to slot forms, or even better, as crescent, as can be seen in curve 2. These are not as favourable as the rectangular valves, but are better than circular/circular overlapping.

If the gas flow is conducted into a vacuum, or with high tank pressures, then as the line intersection begins, sound velocities are reached. The area of overlap is a linear term in equation 1 for the gas mass flow.

$$\dot{m} = (\frac{2}{\kappa+1})^{\frac{1}{\kappa-1}} \cdot \rho^{\star} \cdot \sqrt{\frac{2}{\kappa+1}} \cdot a_1^{\star} \cdot A_{\ddot{u}} \qquad (1)$$

After a substantial time-lapse, the gas flow rate is determined by the pressure-loss within the feed-pipes and control section. The area of overlap is a quadratic term in the calculation of the coefficient of resistance as in eq. 2.

$$\xi = (1-A_{\ddot{u}}/A)^2 \qquad (2)$$

The flow restriction is to be considered additionally. Fig. 3 illustrates the measured and calculated values for a radial control-valve incorporating circular/rectangular overlap cross-sections. The distribution of the pressure-drop for each machine element in % can be seen in Fig. 4. As a result of the deflection of the gas-flow inside the control-valve, it's pressure-loss, when fully open, is relatively high.

FILTER CELL FILLING PROCEDURE

Gas flows into the filter cell while the control valve is open. This causes a built up pressure to be inside the filter cell relative to its environment. The volume of the filter cell and the gas flow rate determine the pressure rise rate. The pressure in the filter cell, which is affected by the gas flow, continues to increase until the filter cloth has been accelerated to such a

velocity that the volume increase of the filter cell corresponds to the volume flow of the gas. The filter cloth is then furhter accelerated while the pressure drops. The cloth attains its maximum velocity when the pressure difference between filtercell and environment becomes zero.

As a result of the filter cake/cloth velocity, the pressure falls below the environmental pressure. Filter cake and cloth then decelerate. The pressure decreases until the volume flow rate of the entering gas again corresponds to the filter cell volume increase. During the further deceleration of the filter cloth, the pressure increases to that of the environment and the procedure starts again from the beginning.

The oscillation thus created, whose frequency and amplitude are dependent on the magnitude of the gas flow, the volume of the filter cell, compressibility of the gas and the mass of the filter cake. This oscillation is superposed upon the translatory motion. In each case the velocity of the translatory motion is the time-related average value of the local cloth velocity. The velocity, averaged in time and over the filter surface, results from the volume increase of the filter cell with respect to the filter surface.

As the distance increases, the motion of the filter cloth is affected by elastic forces caused by the tensioning of the filter cloth. This gives rise to interference oscillations which are dependent upon the filter cell geometry. A minor damping action is caused as a result of energy dissipation in the filter cloth. A significant energy loss is, however, produced by the gas stream which escapes to the environment through the filter cake, particularly then, when cake cracking occurs. The filter cloth oscillation is strongly damped by the escaping compressed air. Further, the oscillation cycle is technically unimportant. One relevant aspect is the fact that the pressure in the filter cell - when the cloth is almost stationary - increases to such an extent that the cake is detached by the filter cell pressure. In some filter cakes, this detachment procedure is additionally supported by a filtrate emergence from the filter cloth, reducing the adhesive stresses between the filter cake and the cloth.

The following section presents the differential equation for the computatation of filter cloth motion. It is solved numerically and indicates a complex dynamic behavior due to the

A new application area for the disc filter is expected in the field of pressure filtration |20,30,31,32|. In such applications, the disc filter possesses other advantages due to its low space requirements and the ability to accommodate large filter areas inside expensive pressure vessels.

To attain the objectives, it is necessary to be able to forecast with certainty how the filtration, dewatering and filter cake discharge processes will behave. The theory of filtration and moisture removal has been dealt with in a number of publications |3,5-36| and are not within the scope of this paper which mainly considers the influence of designed parameters on filter cake discharge.

Reliable removal of the filter cake is of great importance, particularly concerning filters operating in pressurized chambers. Since pressurized chambers are not readily accessible, problems with the removal of the filter cake can impair the operation or even cause a failure of the filter unit. However, even in conventional filters, removal problems may occur, causing a deterioration of throughput and poor residual moisture levels.

DESCRIPTION OF FILTER CAKE DISCHARGE

Adhesive forces cause the filter cake to cling to the filter cloth. These forces must be overcome to permit removal of the filter cake. For this purpose, in disc filters, compressed air from a reservoir is blown in the opposite direction to the filtrate flow through the filtrate piping into the filter cell. This procedure is known as cake discharge by compressed air. The pressure developed in the filter cell in this manner accelerates the filter cloth and the cake adhering to it. After moving a distance of a few mm to a few cm, the filter cloth is tensioned and decelerates with the adhering filter cake. The reduced speed of the filter cloth causes a pressure increase in the filter cell. Simultaneously, inertia forces appear in the filter cake and compressional forces act at its bottom surface, releasing it from the filter surface, provided that the adhesive forces are exceeded.

AIR FLOW THROUGH THE DISC FILTER

For the time being, the compressed air is stored in a reservoir whose volume should be serveral times that of the filtrate pipe and cell. The compressed air line is under pressure as far as the control head. The passage into the filter pipe system is opened to the compressed air in a manner dependent on the rotary speed of the filter and on the control geometry. In many disc filters a magnetically activated quick-opening valve is fitted in the compressed air line before the control head. This valve is intended to ensure rapid opening of the compressed air line particularly in the case of slowly rotating filters.

The air flows through the control head and the filtrate pipe up to the filter cell. The filtrate pipe should be short and have as few bends as possible. An adequate diameter should be selected. The mass flow of the gas is dependent on these design characteristics and on the operating conditions of the filter.

The gas extraction is initiated by the opening of the control head. In the simplest case, this is executed by intersecting the filtrate feed-pipe, with the compressed-air line. Providing both pipes are of circular cross-section, the area of intersection corresponds to that of two overlapping circles. This area (curve 3) is plotted in Fig. 2 as a function of the overlap, which at the instant that the valve is opended, possesses a low gradient.

As to be shown later, it is necessary for the gas flow to be as high as possible when attaining the outside pressure of the filter cell. For this purpose, the time required to fill the cell to the pressure of its vicinity can be exploited. The higher the angular velocity of the filter, the larger is the intersection area during this time-lapse, and the steeper is the function of the intersection angle. The angular velocity may not, of course, exceed the overlap maximum within this interval.

In order to save time and compressed-air necessary to fill the filter cell, an improvement of the discharge has been attempted, by filling the cell to its environmental pressure before introducing the compressed-air pulse. In this case, at the instant that the valve begins to open, the filter cloth movement is initiated, at the area of intersection 0, and at the lowest function of intersection area gradient. A pre air-bleeding of the filter cell is, therefore, for the discharge, often not advantageous, but disadvantageous. An exception of this, however, exists when the filter cake removal is not accomplished through, or with the aid of intertia forces, but owing to the internal pressure

transition of waves, interference oscil-
lations due to differing chord lengths
and the interaction between filter cloth
motion and gas flow as already mentioned
above. However, within the scope of this
paper, the dynamic procedures are only
briefly reviewed. Instead, concrete
design influences from equilibrium sta-
tes of the filter cloth are examined in
some detail.

FORCE EQUILIBRIUM ON THE FILTER CELL

The forces acting on the filter cloth
are shown in Fig. 5. These are the
forces caused by the differential pres-
sure P between the filter cell and the
environment, the elastic forces in the
filter cloth in warp K and weft S direc-
tions, and the inertial force T on
he filter cake. Gravatational force is
neglected. The corresponding force
equations are in z-direciton:

$$d^2F_p = \Delta p \cdot r \cdot d\varphi \cdot dr \qquad (3)$$

for the force due to the pressure

$$d^2K = \varepsilon_r \cdot E_r \cdot \frac{\partial^2 z}{\partial r^2} \cdot r \cdot d\varphi \cdot dr \qquad (4)$$

for the warp cloth force

$$d^2S = \varepsilon_\varphi \cdot E_\varphi \cdot \frac{\partial^2 z}{\partial \varphi^2} \cdot \frac{1}{r} \cdot dr \cdot d\varphi \qquad (5)$$

for the weft cloth force

$$d^2F_T = - m \cdot \frac{\partial^2 z}{\partial t^2} \cdot r dr \cdot d\varphi \qquad (6)$$

for the inertial force. The force
equilibrium in the z direction yields
the differential equation.

$$m \cdot \frac{\partial^2 z}{\partial t^2} = \Delta P + \varepsilon_r \cdot E_r \cdot \frac{\partial^2 z}{\partial r^2} + \varepsilon_\varphi \cdot E_\varphi \frac{1}{r^2}$$
$$\cdot \frac{\partial^2 z}{\partial \varphi^2} \qquad (7)$$

with the elongation of the radial
direction

$$\varepsilon_r = \left| \int_0^{l_o} \sqrt{1 + (\frac{\partial z}{\partial r})^2} \cdot dr - l_o \right| \cdot \frac{1}{l_o} \qquad (8)$$

and the angular elongation

$$\varepsilon_\varphi = \left| \int_0^{\varphi_o} \sqrt{1 + (\frac{\partial z}{\partial \varphi})^2} \cdot d\varphi - \varphi_o \right| \cdot \frac{1}{\varphi_o} \qquad (9)$$

The differential pressue results from
the mass flow into the filter cell and
from the ideal gas law

$$\Delta p = \frac{R.T. (m_{Lo} + \int_0^t (\dot{m}_{L1} - \dot{m}_{L2}) \cdot dt}{V} \qquad (10)$$

FILTER CLOTH STATIC EQUILIBRIUM

The bulge distortion of the filter cloth
is accompanied by elastic stresses in
the described manner. In a static ela-
sticity calculation for the filter
cloth, i.e. neglecting the inertial forces
in equation 7, the elastic stresses
in the cloth are in equilibrium with
the pressure in the filter cell. Pro-
vided the dynamic effects on the geo-
metric structure of the filter cloth
are ignored, this equilibrium pressure
corresponds to an average tension com-
ponent developed by the filter cloth to
counteract the pressure in the filter
cell and the inertial forces of the
filter cake.

Providing that the pressure component
is not reduced because of its ability to
act on only a limited portion of the
bottom surface of the filter cake as a
result of the pore structure.

The magnitude of these stresses also
corresponds to the filter cake stress
caused by pressure and inertial forces.
A curve of this equilibrium pressure
plotted over the space and volume of
the filter cloth is a significant para-
meter for the detachment of the filter
cake. The influence of several filter
cell parameters on this distribution
will be discussed below.

EFFECTS OF THE CELL ANGLE

In Fig. 6 the pressue in the filter
cell is shown as a function of the bulge
volume of the filter cloth. The curves
shown in the diagram vary with the angle
of the filter cell. It can be clearly
seen that as the angle of the filter
cell increases, the quantity of air
that is necessary for the attainment
of a desired cell pressure level in-
creases also. Thus, with the same fil-
ter cell piping, large cell angles
require longer control valve opening

times or lower filter speeds and
greater quantities of compressed air.
The reason for this behavior is that
the forces directed vertically onto
the filter cloth can only be absorbed
by a curvature of the cloth, the radius
of which decreasing with increasing
restraint length.

For existing filter cells with large
centric angles, this can be remedied by
reducing the restraint length of the
filter cloth, by attaching strips to
the filter cell to hold the cloth down.

These strips can traverse the filter
cell either laterally or longitudinally.
Fig. 7 shows the extensions in a longi-
tudinal direction plotted against those
in the lateral direction. The extension-
sions in the longitudinal direction plo-
ted against those in the later direc-
ion. It can therefore be advisable to
attach strips to the filter cell on a
transverse direction in order to increase
the stresses in the longitudinal fibres
of the filter cloth so that they can
also siginificantly contribute to the
deceleration of the filter cloth instead
of the transverse fibres only which would
otherwise prematurely break.

EFFECT OF THE MODULES OF ELASTICITY

The pressure in the filter cell is plot-
ted against the displacement volume for
filter cloth modulus of elasticity
between 1×10^5 and 1×10^6 N/m in Fig.
8. The idagram indicates that the modulus
of elasticity can contribute signifi-
cantly to the rapid increase of the
cell pressure. In the case of an inade-
quate compressed air supply configura-
.on, the selection of a filter cloth
with a large modulus of elasticity can
result in an improvement in cake dis-
charge.

EFFECT OF PRETENSIONING THE FILTER CLOTH

The filter cloth can be tensioned in
the longitudinal or traverse direction
or can be left loose. Fig. 9 shows an
example for pretensioning in the trans-
verse direction. The cell pressure is
again plotted against the bulge volume
of the filter cloth. The mean curve
represents the typical case of the fil-
ter cloth lying flat on the filter cell
without pretensioning. If the cloth is
stretched about 1%, an appreciably
more rapid pressure increase takes
place. This can be advantageous for

an underdimensioned compressed air
supply. The cloth, whose angle is about
0.5% larger than the cell angle, can
also be advantageous. It offers a wide
range in which the pressure hardly
increases. A high filter cloth speed
can be attained in this range which, as
a result of the abrupt change of direc-
tion with a pronounced pressure in-
crease, results in a rapid filter cloth
deceleration. However, for this purpose,
large quantities of compressed air must
be available over a relatively long
period of time.

Fig. 10 shows the pretensioning in a
longitudinal direction. It shows that
in this case, a noticeable effect is
only obtained with impracticably high
pretensioning values. In order to
attain other results, the longitudinal
direction of the filter cloth must be
subdivided. However, it must be men-
tioned that the pretensioning values in
both the transverse and longitudinal
direcitons are limited by the plastic
flow of the filter cloth.

EFFECTS OF THE CELL VOLUME

All the factors discussed have one
thing in common. In all cases, a fil-
ter cake discharge improvement was
achieved in that the curve slope of
the pressure increase relative to the
filter cell volume became steeper. In
other words, a higher pressure was
developed in the filter cell with the
same quantitiy of compressed air. In
Fig. 11 the volume of the 33º test
cell is plotted against the pressure
in the filter cell. The continuous
curve represents the equilibrium con-
dition. Triangular symbols indicate
the theoretical curve geometry when
the inertial forces are taken into
account. Apart from the oscillations
at the start of the cycle, the pres-
sure curve virtually follows the
shape of the equilibrium curve. In the
case of the respective filter cell,
only the attainable pressure is signi-
ficant. The inertial forces correspond
to the deviation of the symbols from
the equilibrium curve and are negligibly
small.

In the case of large gas flow rates or
small cell volumes, oscillation around
the static equilibrium occur (Fig. 12)
due to the inertia forces. The pressure
variation from static equilibrium in
the filter cell, acting upon the filter
cake, conformes with the area inertia
as calculated by eq. 5. In this instance,
inertia forces must be taken into
consideration.

EXPERIMENTAL RESULTS

Fig. 13 shows experimental results for cell angles of 33°, 22.5° and 10°. The abscissa represents the pressure in the compressed air reservoir and the ordinate the mass ratio of filter cake discharge to filter cake disposition. The 10° cell begins to discharge at a pressure of O.4 bar and throws the filter cake off completely at 1.3 bar. The 33° cell only starts to discharge at 2.3 bar and will not throw off the entire filter cake below 3.O bar.

Fig. 14 shows the removed cake fraction plotted against the discharge pressure for the 33° cell with and without cloth restraint. An improvement of the filter cake discharge can be seen. Due to the considerable border length of the attached strip on the relatively small filter surface of the test cell, the filter cake – even though it has been completely detached from the filter cloth – is still retained by the strip. Thus, the improvement in the diagram is less pronounced than it would be in the case of larger filter cells.

Fig. 15 shows the experimental results for a pretensioned filter cloth. The pressure required for a complete discharge is reduced by about O.5 bar when the filter cloth is pretensioned.

An experiment in which the filter cell was filled with spheres in order to reduce the cell volume is shown in Fig. 16. The pressure for 100% discharge from the cell whose volume was reduced by 45% is considerably lower than the pressure required for 100% discharge of the unfilled filter cell.

SUMMARY

The article shows that the pressure variation in a filter cell, in which relatively low air streams are applied, corresponds to the equilibrium pressure needed to bulge the filter cloth to a particular bulge displacement volume. In these cases, the variation of the equilibrium pressure with the filter cloth bulge volume is significant. This is the case in many currently operating disc filters.

However, in the case of filter cells of small volume or with large gas flows, inertia forces are significantly involved in cake release.

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FORMULAE

a_1^*	sound velocity	$|m/s|$
A	area	$|m2|$
$A_{\ddot{u}}$	intersection area	$|m2|$
E	elasticity modulus	$|N/m|$
F	force	$|N|$
K	warp cloth force	$|N|$
m	filter cake mass per area	$|kg/m^2|$
l	filter cell length	$|m|$
m_{Lo}^o	initial mass of gas in the filter cell	$|kg|$
$\dot{m}_{L1}$	gas flow into the filter cell	$|kg/s|$
$\dot{m}_{L2}$	gas flow out of the fil- ter cell	$|kg/s|$
P	pressure	$|N/m2|$
R	gas constant	$|J/kg\,^oK|$
r	coordinate	$|m|$
S	weft cloth force	$|N|$
T (index)	inertia	
T	temperatur	$|^oK|$
t	time	$|s|$
V	volume of filter cell	$|m3|$
Z	coordinate	$|m|$
Δ	difference	
ε	elongation	$|-|$
	coordinate	$|o|$
ρ	density	$|kg/m^3|$
κ	polytrope coefficient	$|-|$
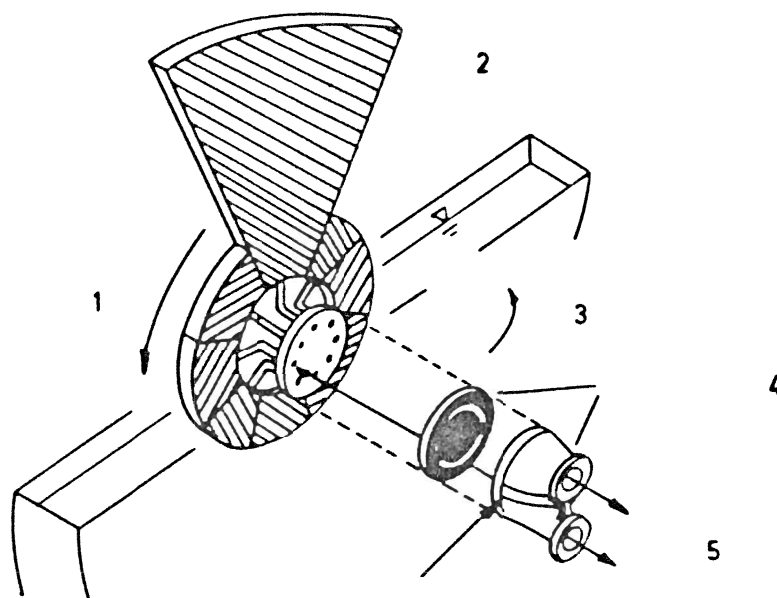
Figure 1:

Principle of disc filter apparatus

1 Discharge of filter cake
2 Dewatering
3 Cake formation
4 Pressure pipe
5 Control head
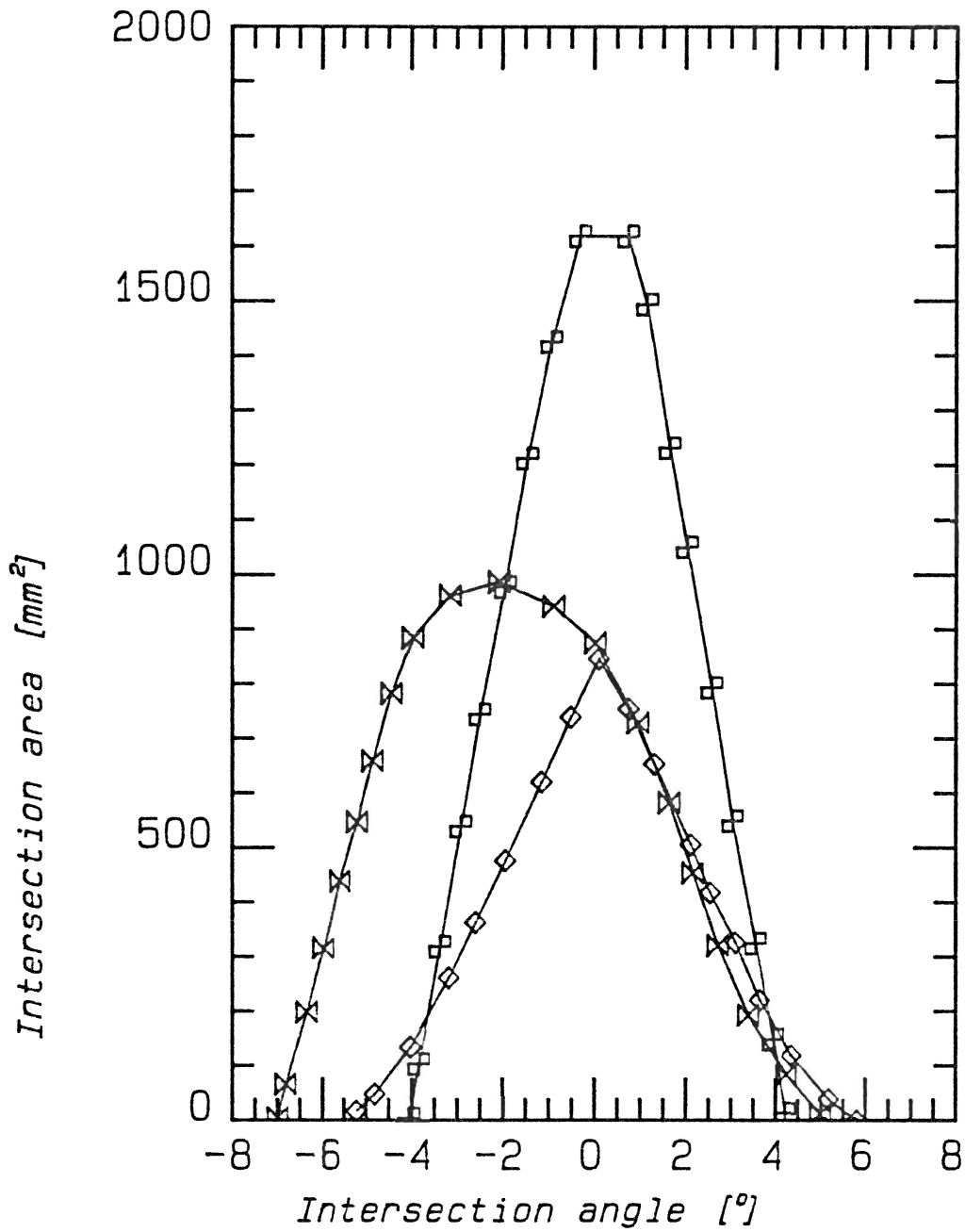
Figure 2:

Different control head geometries

⌐ *retangle (1)*
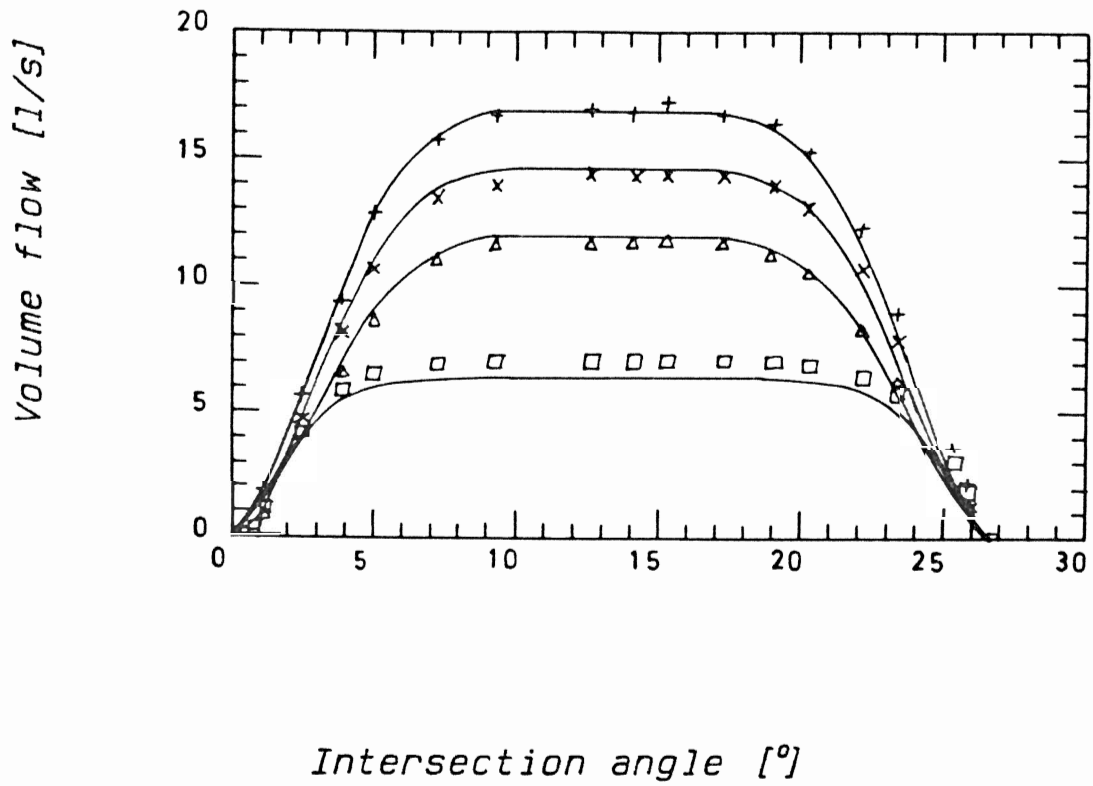
⋈ *crescent (2)*

◇ *circle (3)*

Figure 3:

Volume flow as a function fo intersection angle

+ 0.20 Bar
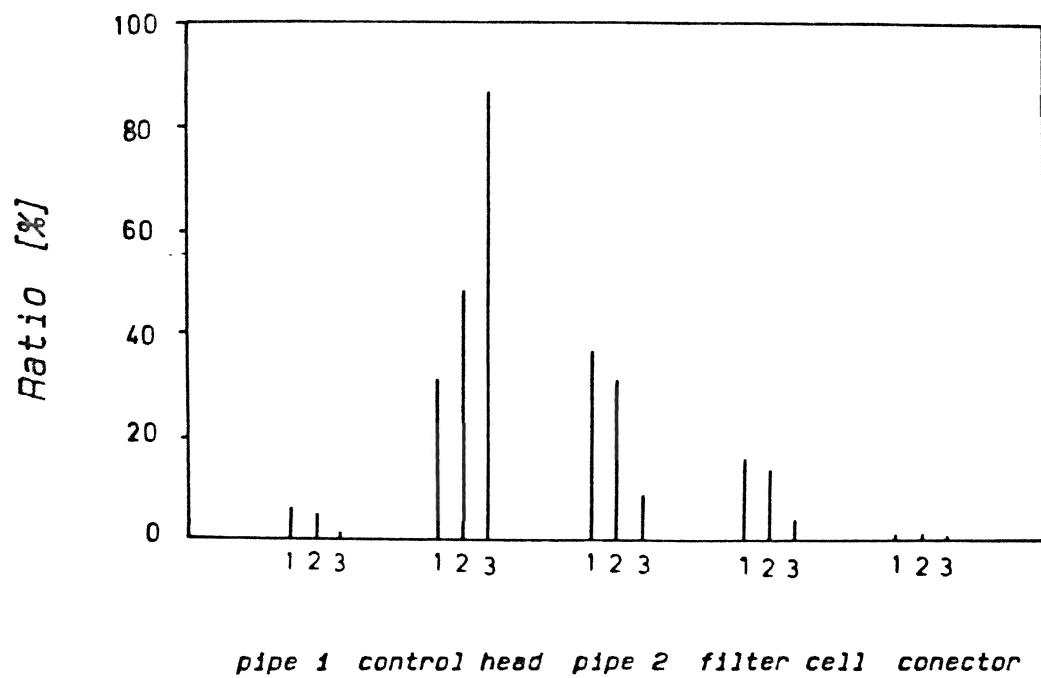× 0.15 Bar
△ 0.10 Bar
□ 0.05 Bar

Figure 4:

_____

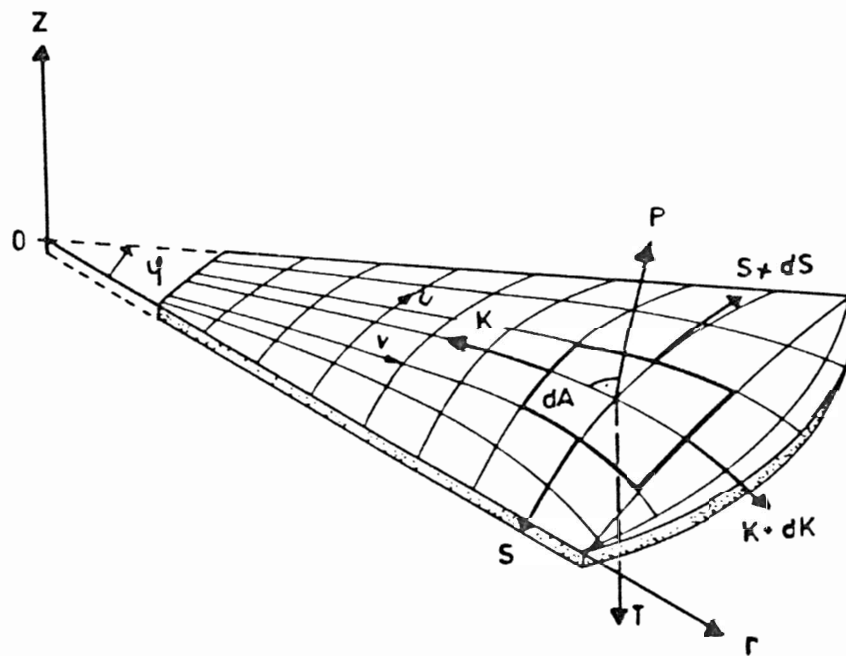Ratio of flow resistance

1 open
2 half open
3 quater open

Figure 5:

Forces acting on the filter cloth

P   : Pressure
S, K   : Elastic forces
T   : Inertia force
u, v, r, φ : Coordinates
dA   : Differential area
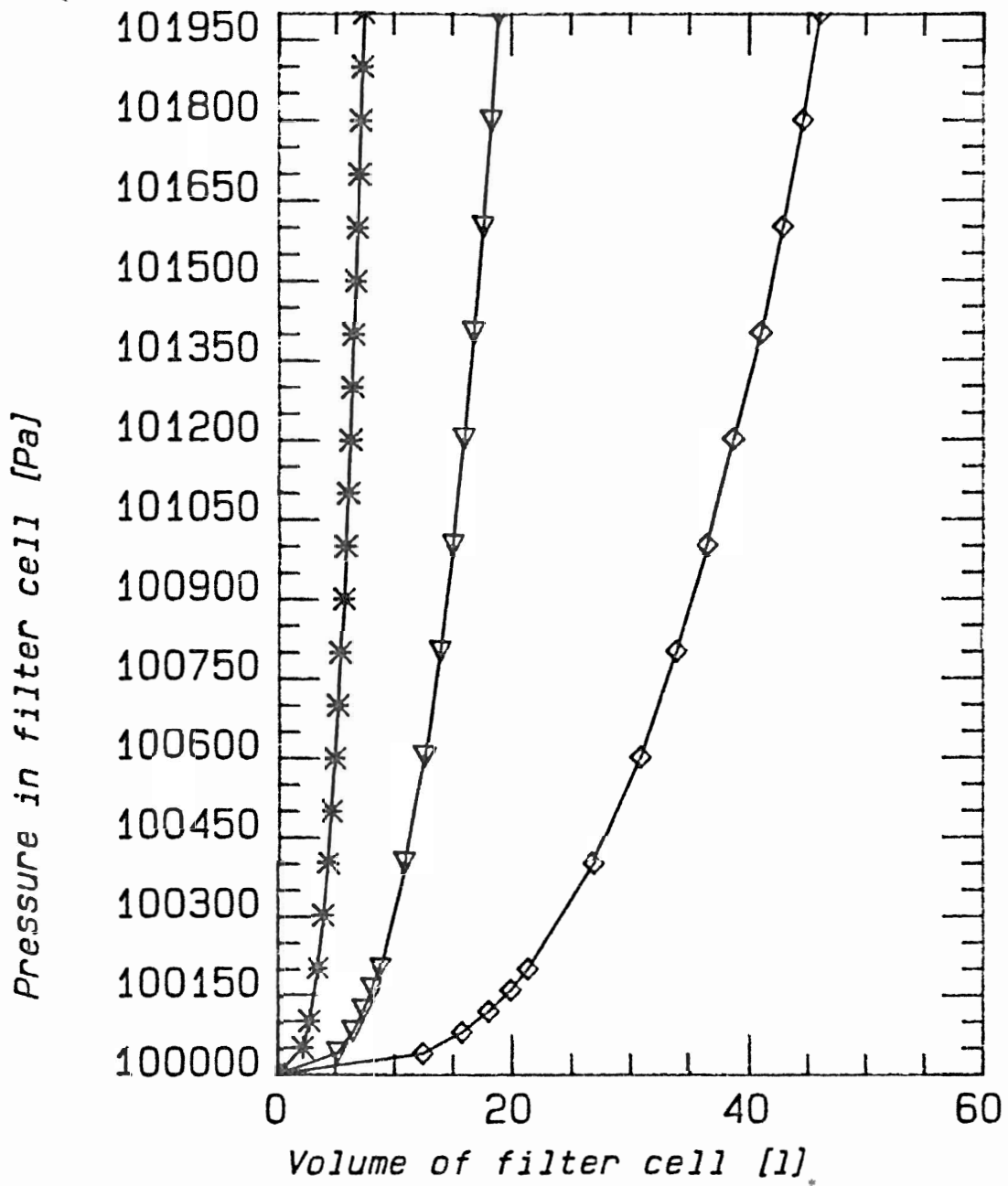
Figure 6:

Influence of filter angle

* 12 Grad
▽ 20 Grad
◇ 30 Grad
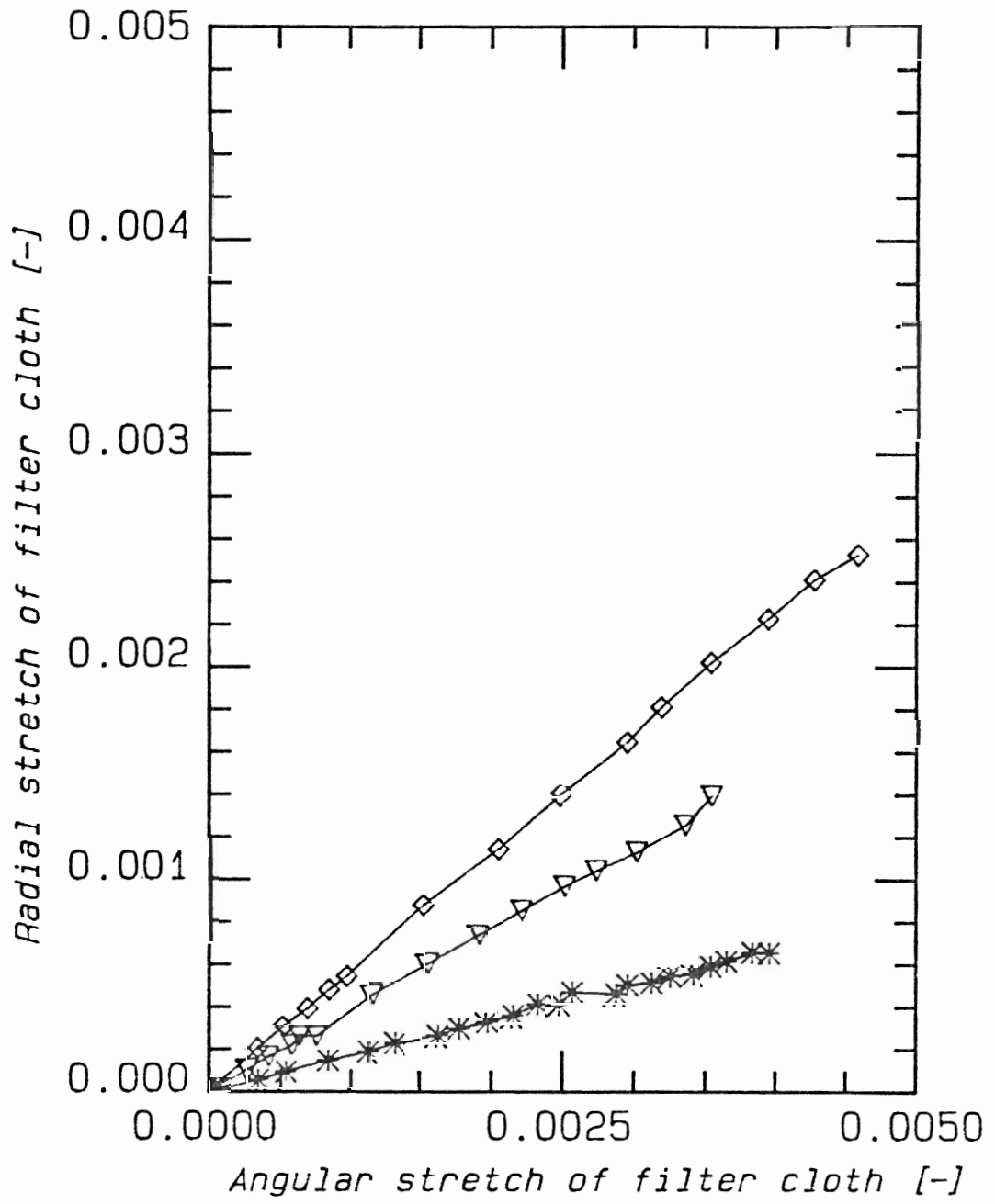
Figure 7:

Influence of filter angle

* 12 Grad
▽ 20 Grad
◇ 30 Grad
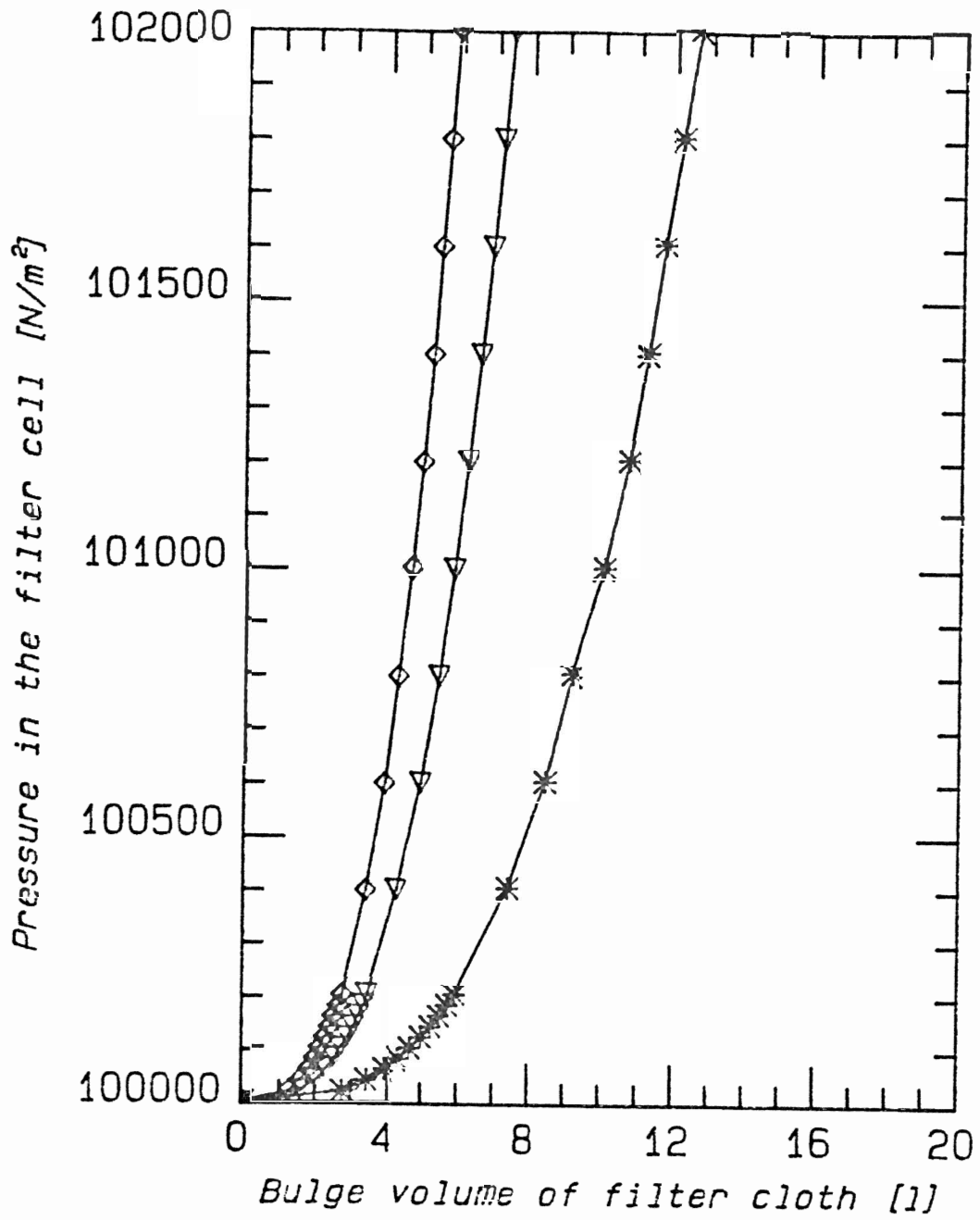
Figure 8:

Influence of the modulus of elasticity

Modulus of elasticity
* $1*10^5$ [N/m²]
▽ $5*10^5$ [N/m²]
◇ $1*10^6$ [N/m²]
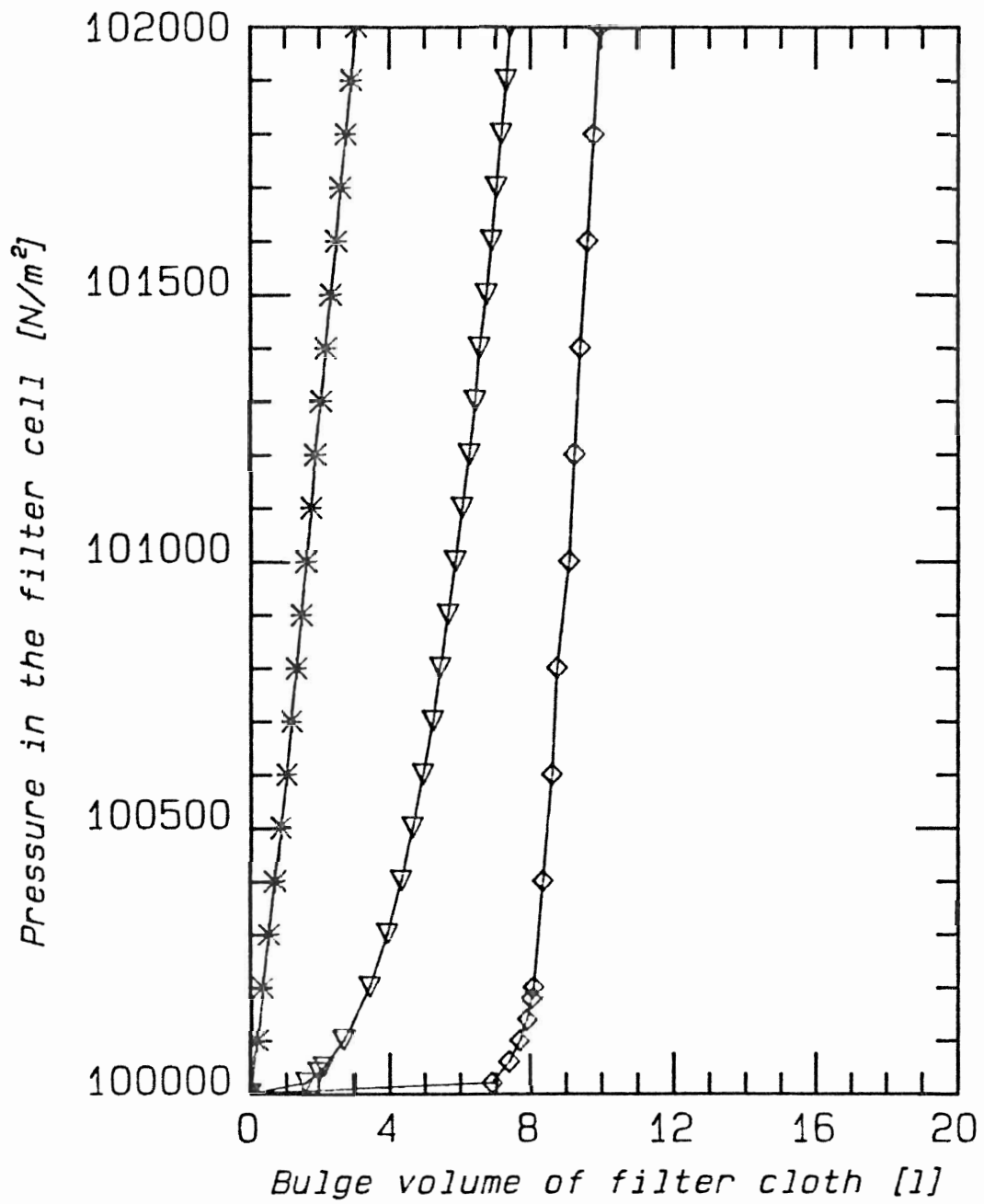
Figure 9:

Influence of initial angular stretch

Initial stretch
*   .9 [%]
▽   .0 [%]
◇ −.5 [%]
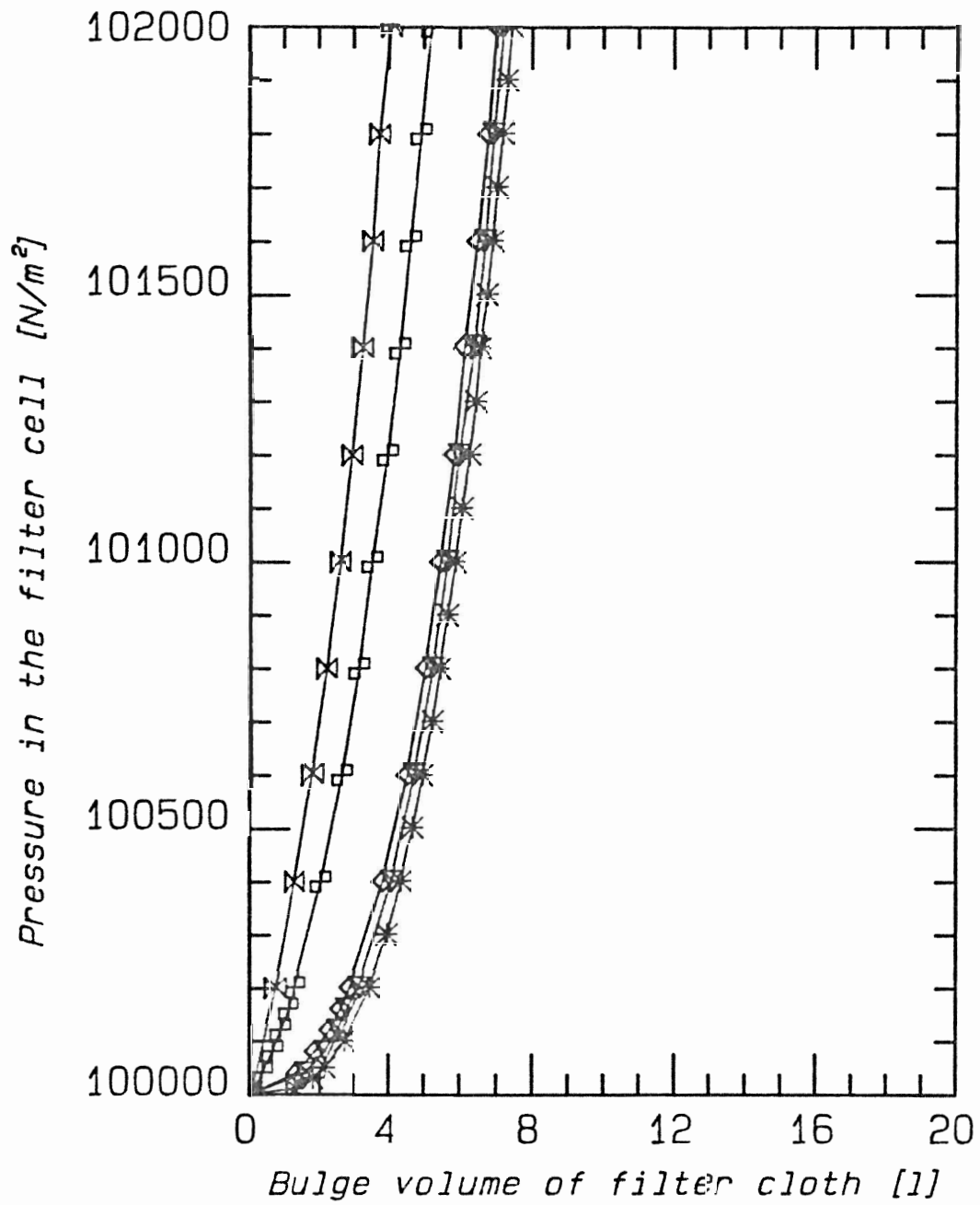
Figure 10:

Influence of initial radial stretch

Initial stretch
⚹   .0 [%]
▽   .3 [%]
◇   .6 [%]
⊞   6.0 [%]
⋈   13.0 [%]
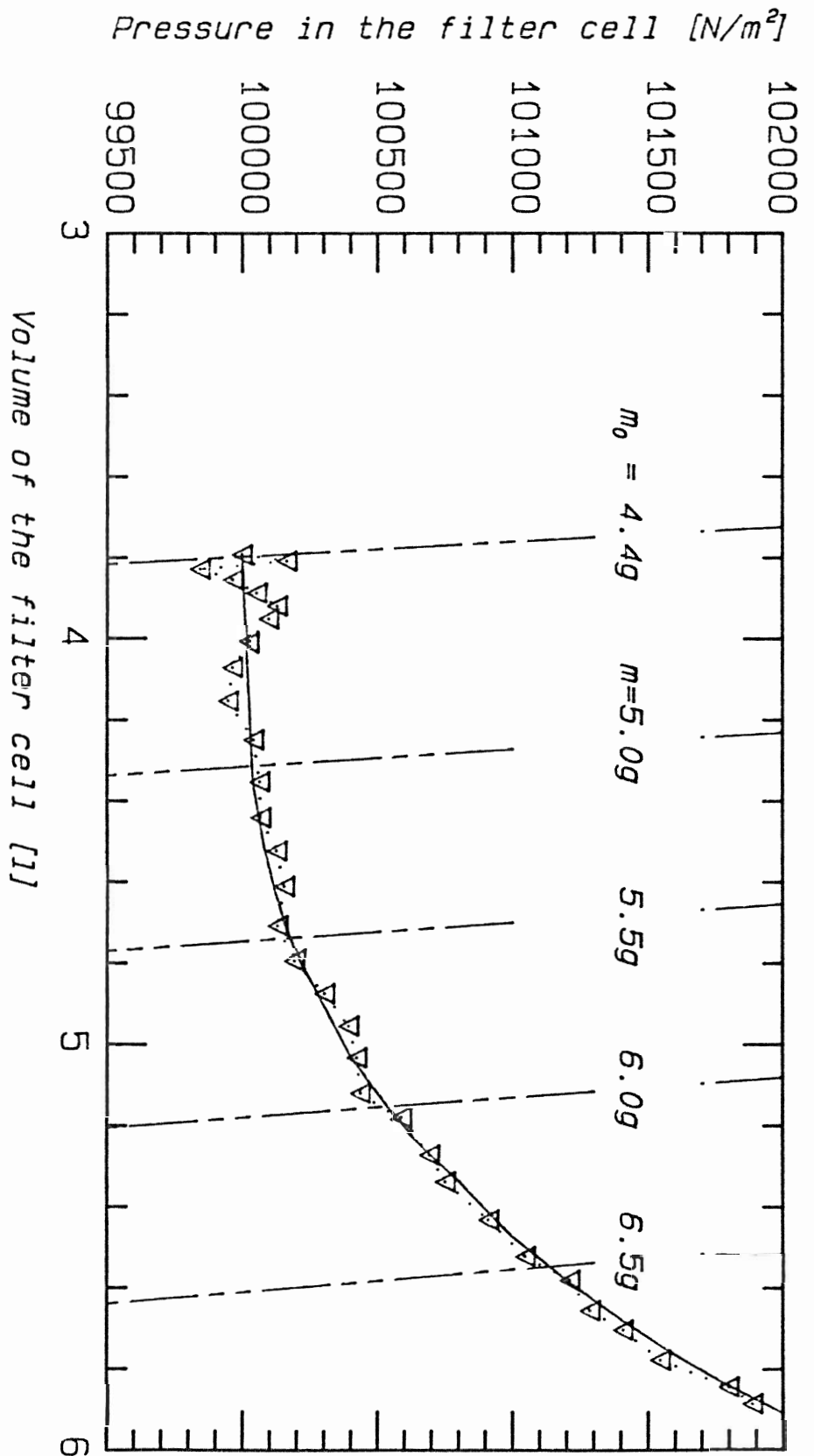
Figure 11: Experimental cell with 33° angle
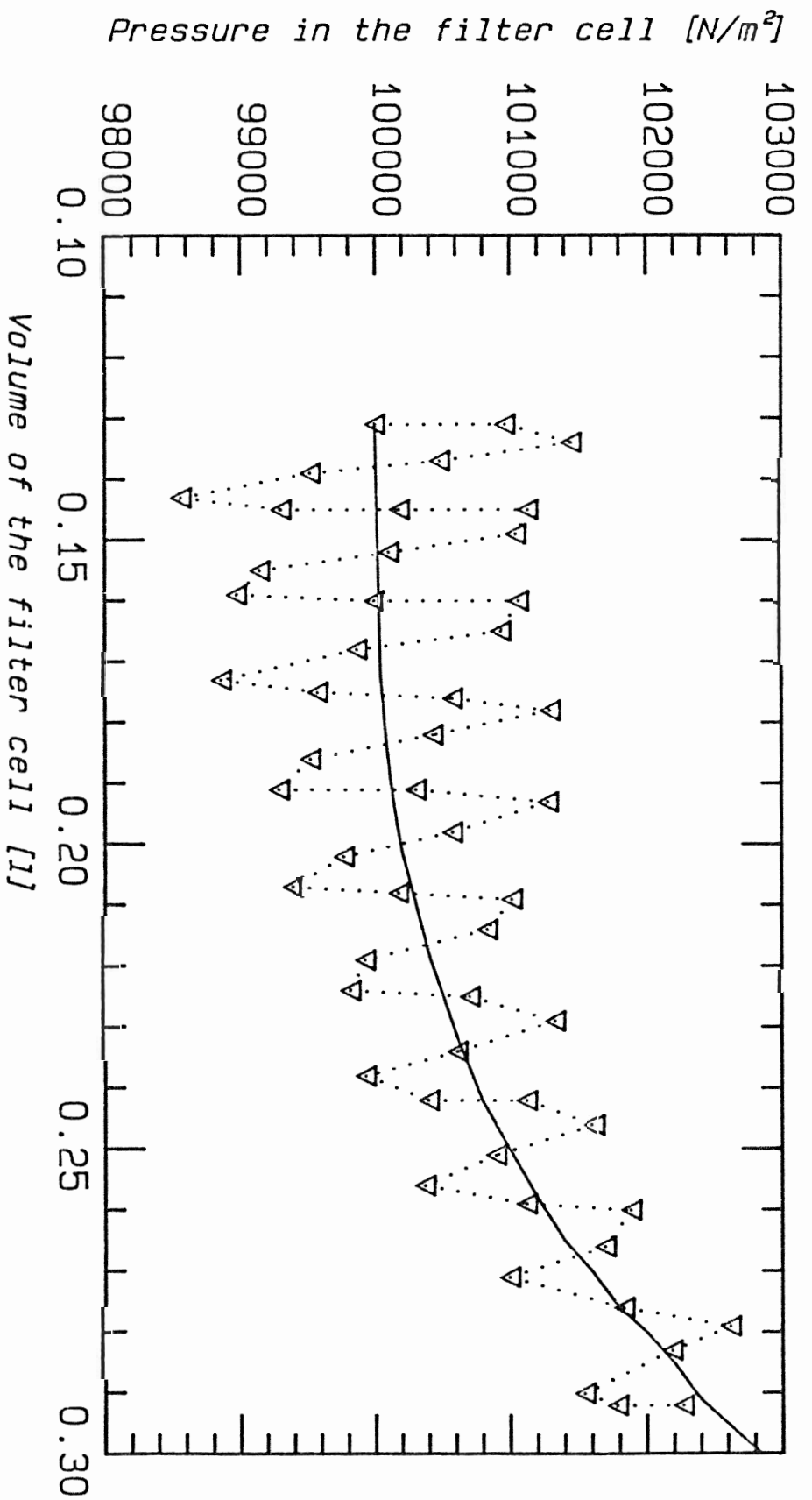------------ static balance
△ gas mass flow 0.008 kg/s

Pressure in the filter cell [N/m²]

Volume of the filter cell [l]

$m_0 = 4.4g$ $m=5.0g$ $5.5g$ $6.0g$ $6.5g$

Figure 12:

Experimental cell with 10° angle

------- static balance

▽ gas mass flow 0.008 kg/s

Ratio of detached filter cake [%]

100

75

50

25

0

0.0   0.5   1.0   1.5   2.0   2.5   3.0

Pressure in the pressure vessel [bar]
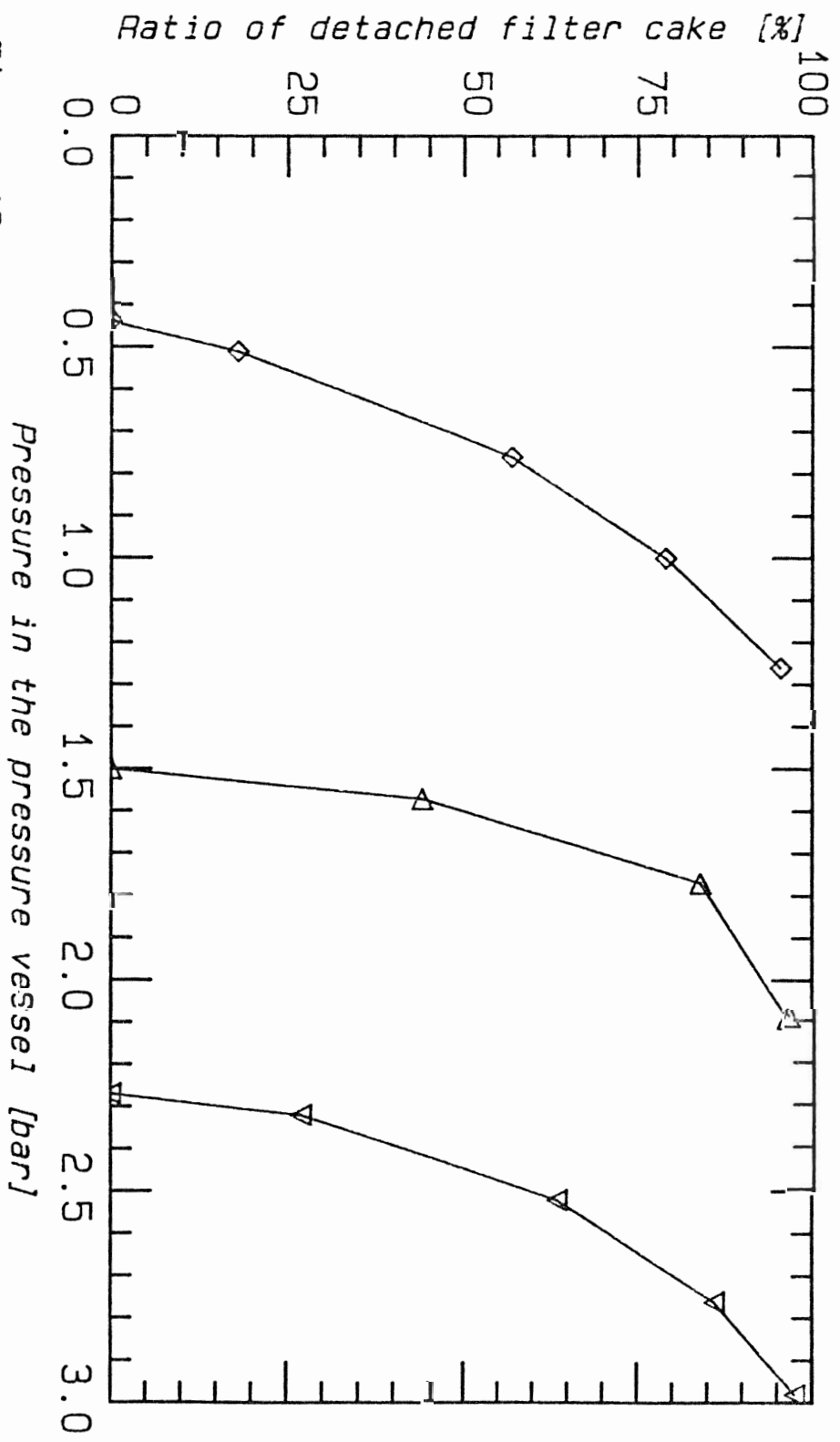
Figure 13:

Experimental results of different filter angles

▽ 33° Grad
△ 20° Grad
◇ 10° Grad
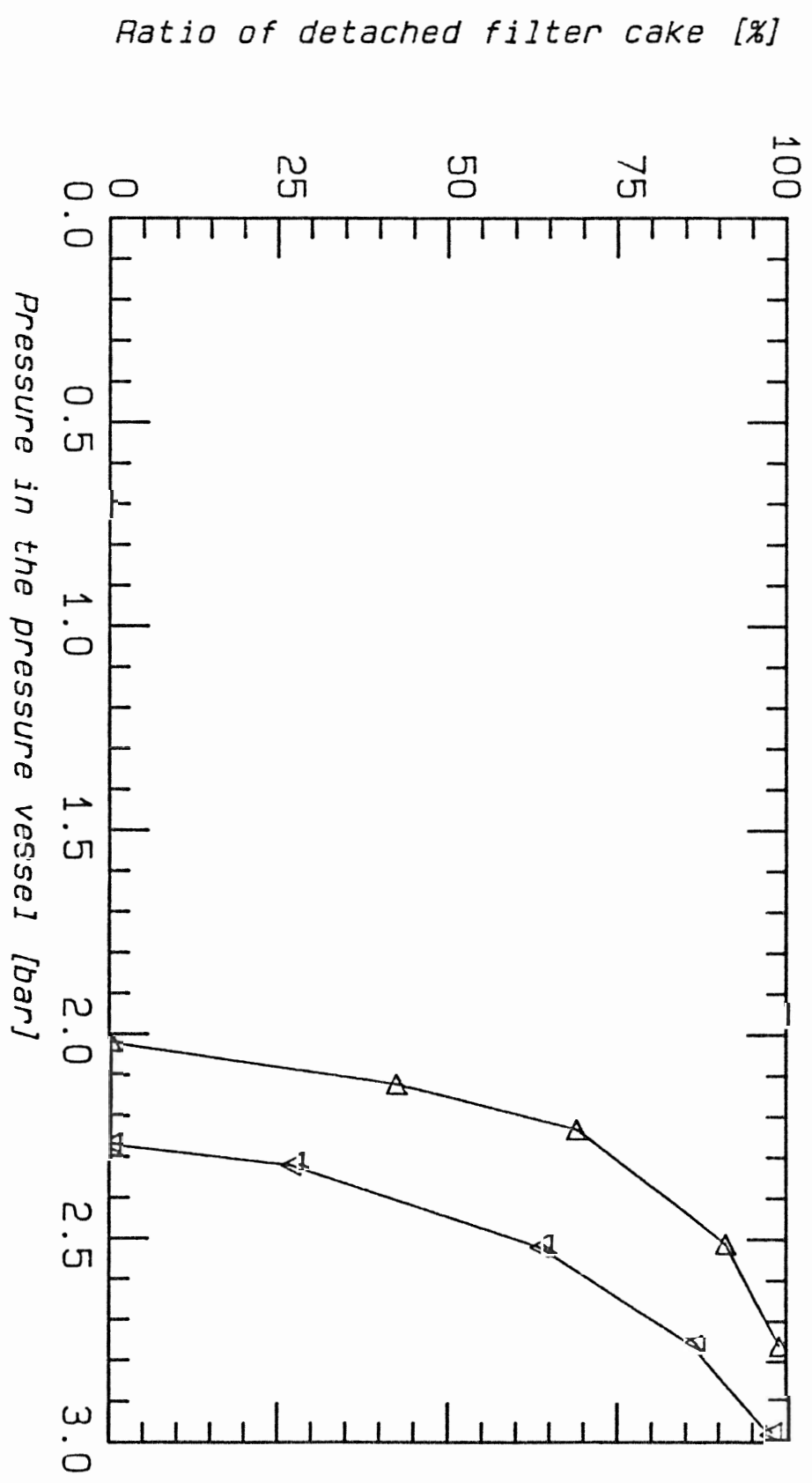
Figure 14: Experimental results of a fixed filter cloth
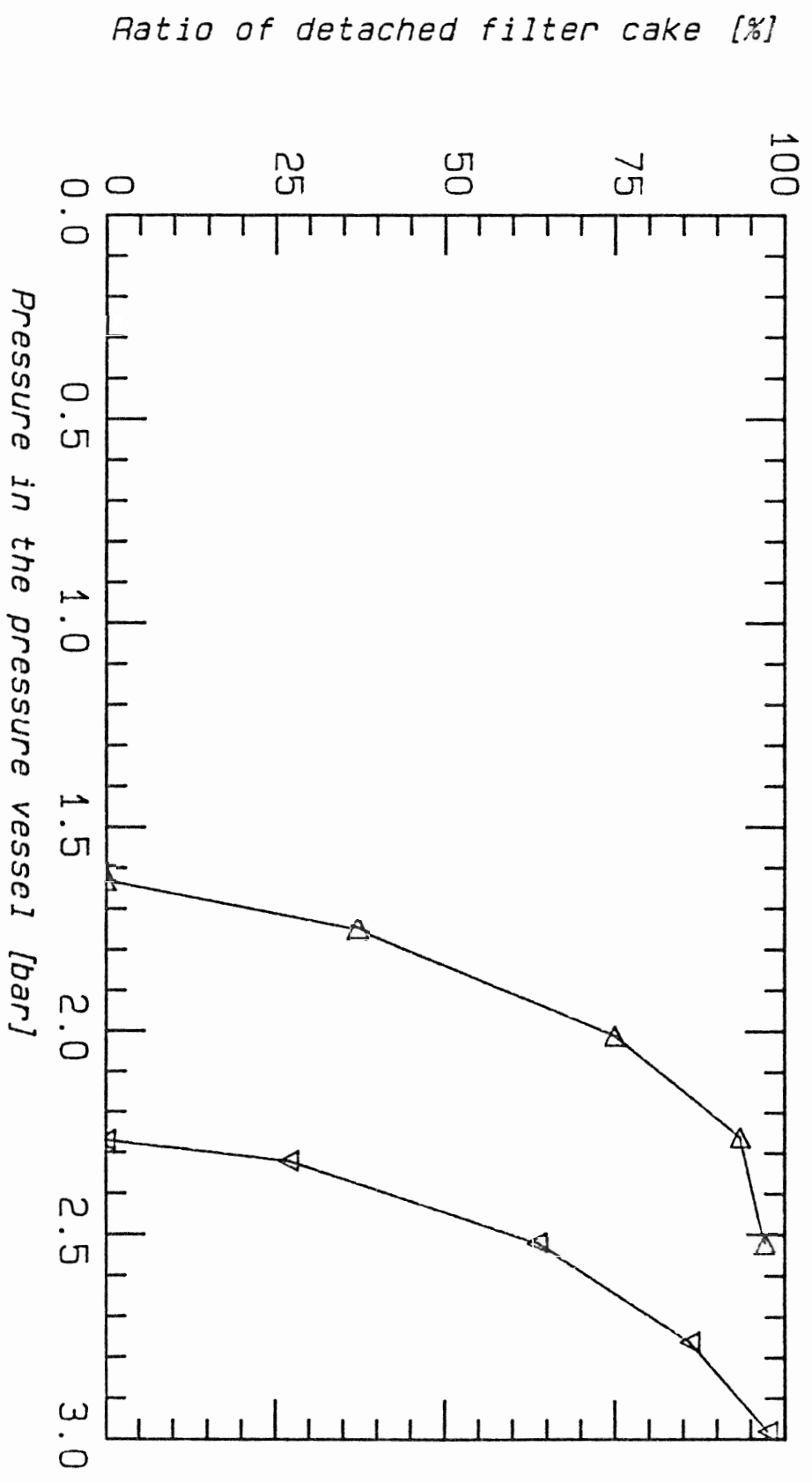
▽ 33° Grad

△ 33° Grad (fixed filter cloth)

Figure 15:   Experimental result of a filter cloth with initial stretch

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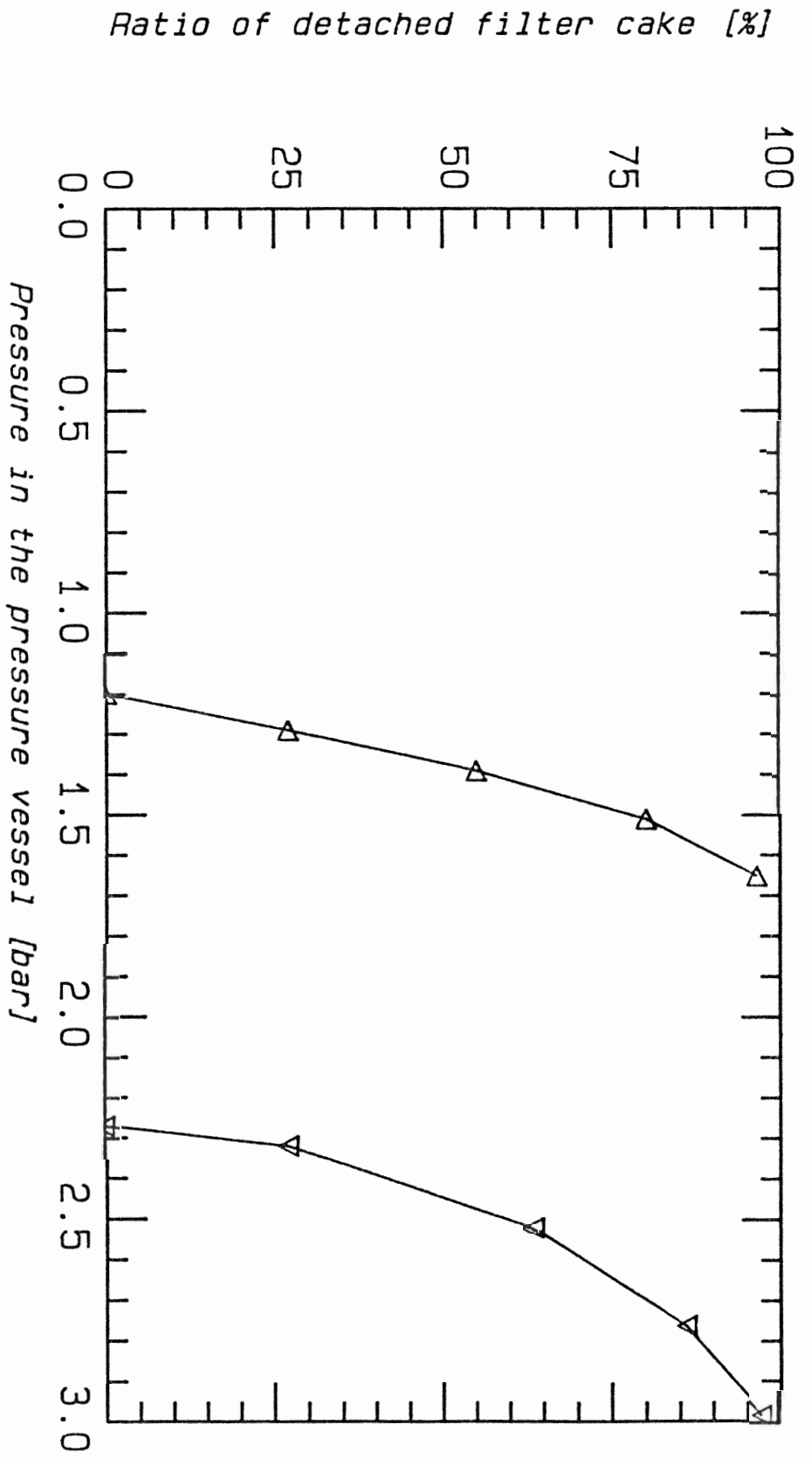▼ without initial stretch
▲ with initial stretch

Figure 16:

Experimental result of a filter cell filled with spheres

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▽ filter cell empty
△ filter cell filled up