The

Matematica approach;

1. **Optimal Design.**
2. **Accurate Manufacturing.**
3. **Optimal installation in tube.**
4. **Optimal Instrumentation.**
5. **Calculation of the flow with the Matematica algorithm.**

makes Scientific Flow

measurement in tubes with

0.7 % uncertainty

of actual flow

from 10 to 100% flow

with throat devices possible.

Contact Matematica or read this

manual to understand how it's achieved.

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Date: 2003-03-25

Matematica, Nordostpassagen 46, S-413 11 Göteborg, Sverige

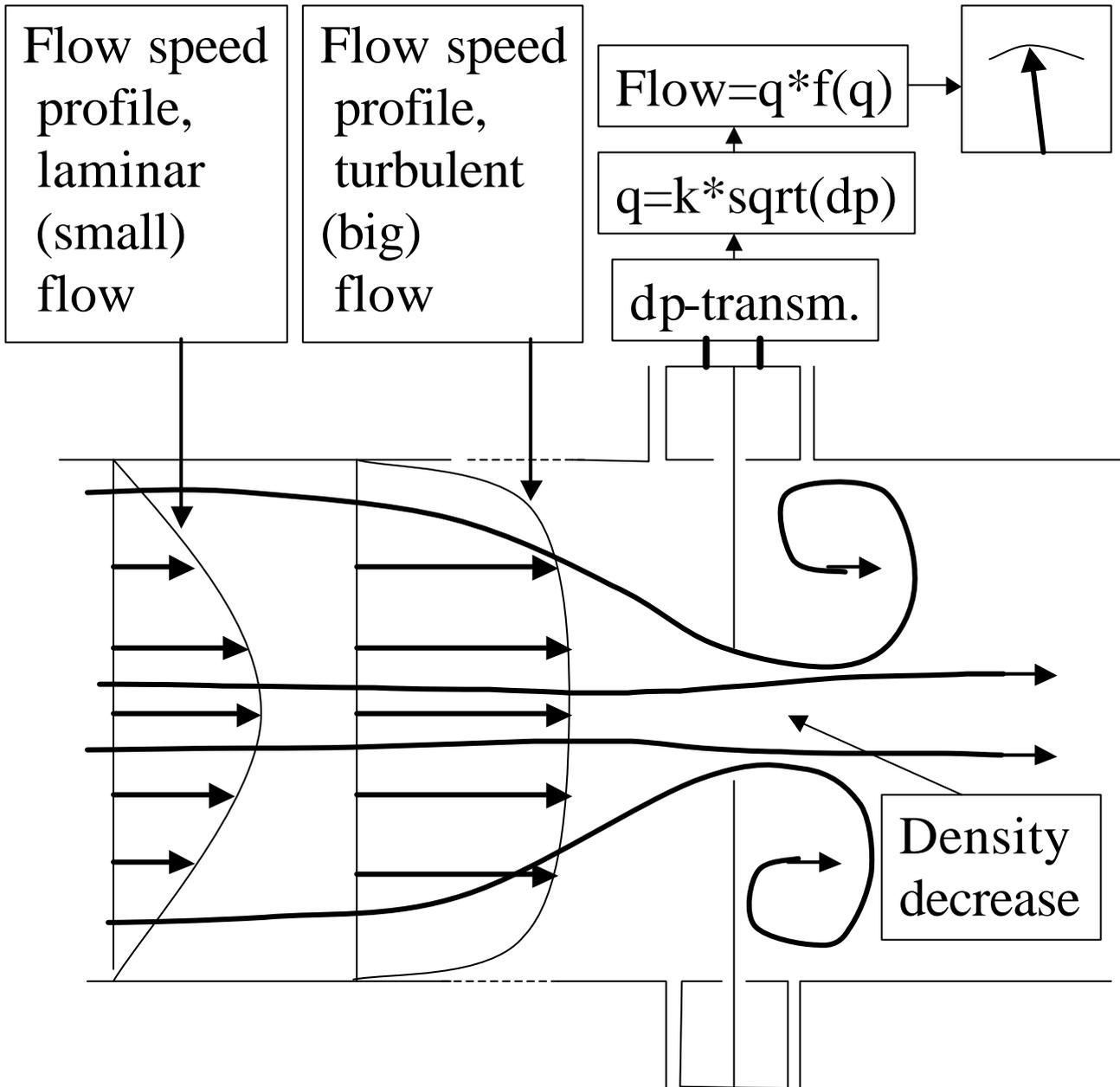| Flow speed profile, laminar (small) flow	Flow speed profile, turbulent (big) flow	Flow=q*f(q)

q=k*sqrt(dp)

dp-transm.

Density decrease

Fig 1. Flow measurement in a tube with orifice plate.

1. Introduction

This manual will show how to measure flow in tubes with throat devices.

The environment can be everything from industrial plants to laboratories.
The performance of the flow measurement can be as good as <u>0.7 % uncertainty of</u>
<u>actual flow</u> from 10 to 100% flow if;

6. **Design.**
7. **Manufacturing.**
8. **Installation in tube.**
9. **Instrumentation.**
10. **Calculation of the flow.**

is done according to the <u>Matematica approach</u>.
The Matematica approach gives You full control over every parameter that have
an impact on Your flow measurement.
<u>Over 20 parameters, like physical properties of the fluid, pipe roughness,</u>
<u>installation in tube, differential pressure transmitter performance has to be</u>
<u>under Your control, or the flow measurement will malfunction.</u>
<u>It cannot perform better then the weakest part.</u>
The Matematica approach is described here , step by step, and every step
is calculated and described by the computer software Processline from Matematica.
The calculations are based on scientific documentation, like the standard ISO 5167-1
from 1991, amendment 1 from 1998 and german VDI/VDE journals 2040 & 2041,
it means very good credibility.
The flow must be a one phase flow, it means the fluid can be a gas (-mixture)
or a liquid (-mixture), but not a gas-liquid mixture.
I will also show how to improve old installations of throat -devices.
This is done by identification and reduction of the
biggest error-sources and, if needed, improvement of the square root
flow calculation by a <u>new algorithm called the Matematica algorithm</u>.
This algorithm is a correction of the square root function, and <u>can reduce the flow-</u>
<u>calculation error for gases from sometimes 10% to 0%.</u>
This algorithm can be keye d into any modern computer as a function-block.

2. The potential of the ISO5167-standard.

2.1 Uncertainties
Smallest possible uncertainties for some throat devices;

Orifice plate	**0.5 % of actual flow**
ISA 1932 nozzle	**0.8 %**
Classical Venturi tube;	
-Rough cast convergent	**0.7 %**
-Machined convergent	**1.0 %**
-Welded	**1.5 %**
Venturi Nozzle	**1.2 %**

2.2 Span
The best possible relations between minimal and maximal flow;

Orifice plate	**1-20000**

ISA 1932 nozzle	**1-50**
Classical Venturi tube;	
-Rough cast convergent	**1-10**
-Machined convergent	**1-5**
-Welded	**1-14**
Venturi Nozzle	**1-13**

It means the orifice plate has the best possible accuracy and span (but not pressure loss);

Uncertainty	**0.5 % of actual flow**
Span	**0.05-100 % flow**

Note; This is the best possible performance according to the standard.
Unfortunately the total flow measurement uncertainty consists of many other uncerainty
Contributions from dp-transmitter, tube, throat size and more.
Therefor, in practice, the total flow uncertainty adds up to best possible <u>0.7 % of actual</u>
<u>flow.</u>

<u>2.3 How to use this potential.</u>
With the Matematica approach concerning;

1. **Design.**
2. **Manufacturing.**
3. **Installation in tube.**
4. **Instrumentation.**
5. **Calculation of the flow with Matematica algorithm.**

you can measure with 0.7 % total uncertainty of actual flow from 10 to 100% flow.
How it's done is described in the next chapter 3.

<u>3 Optimal design, installation, instrumentation and flow-calculation.</u>

<u>3.1 Design</u>

To be as concrete as possible, please study the following flow;

Example 1;

Fluid	**Steam at 200 C/ 300 kPa absolute**
Flow	**0.3-3 ton/h**
Straight length at disposal	**10 m after 90 degree bend.**

Our task is to measure as good as possible, no matter what the cost.
It means free hands to design everything that has an impact on the
flow-measurement accuracy, like tube size, differential pressure transmitter and more.

Let's make an optimization with the following restrictions;

Throat devices	**no restriction**
Tubesize	**100-500 mm**

Differential pressure   **1-11 kPa**
Straight length at disposal   **10 m after 90 degree bend.**
**Processline computer software then tests over 1000 possible design's and reports the one
that meets our demands best, it means best possible average accuracy from 0,3 to 3 ton/h.**

Processline report;
Optimal primary device: Orifice plate (Corner tappings)
Optimal throatdiameter d cold (=20 C)   (mm)= 175.71
Optimal tubediameter D cold (=20 C)   (mm)=   300
Optimal maximal differential pressure   (kPa)=   1
Optimal Pos. of upstream pressuretapping after fitting.(m)=   7.2

**This is the best possible design. It means a big tube size and
a small differential pressure.**

3.2 Manufacturing
**The manufacturing of the orifice plate is exactly described in the standard.
The only comment here is if You have an orifice plate/corner tappings
with a carrier ring the diameter of the ring must be equal or bigger than the
diameter of the tube (within standard limits).**

3.3 Installation
**Now it's time for installation in the tube.
Let's take a look at the standard.
For 0 % additional uncertainty, the throat device must be
installed with the following precision;
Max eccentricity tube/throat 0% add. Error____(mm)=   2.03
Maximal angle tube/throat_____=1 DEGREE
Also the carrier ring and bearings must be flushed with or
outside the tubewall everywhere!**

3.4 Instrumentation
**After installation it's time to instrument the throat device.
The instrument(s) needed is a differential pressure transmitter (dp transmitter)
(and sometimes a pressure and temperature transmitter).**

3.4.1 Differential pressure transmitter.
**Today You can get a commercial dp transmitter with an output signal (4-20 mA)
uncertainty of 0.10% of maximal differential pressure, at laboratory environment.
In industrial environment with big changes in ambient temperature and fluid
static pressure, the uncertainty will increase, but can be controlled with the Matematica
approach. Please contact Matematica for details.
Is this precision enough and where do I put the square root function,
in the dp-transmitter or in the 4-20mA receiving computer (if any)?
Let's take a look of an Error/uncertainty Processline calculation (Table 3.4.1)
This table shows how different errors/uncertainties impacts on the flow measurement,
with the uncertainty contribution from the dp-transmitter underlined.**

In the left column You have the Error/Uncertainty-source, like (see fig. 1b);
1. dp transmitter % of maximal dp (=differential pressure transmitter % of maximal differential pressure).
The n the second column defines the size of the uncertainties/errors (like 0.1),
and column 3 to 12 shows the impact from each error/uncertainy source on the flow measurement at 10, 20, 30....100 % of maximal flow (=3 ton/h for our example).
At the last row all error/uncertainty contributions are summarized to a
total flow measurement uncertainty, calculated by geometric addition of
all uncertainties (=sqrt(e1*e1+e2*e2....) plus arithmetic addition of all errors +(e1+e2...).
The average total uncertainty is 0.77% of <u>actual</u> flo<u>w</u> with worst case 5.03% at 10% flow.
As You can see, <0.7% uncertainty of actual flow is fulfilled between 35 and 100% flow, all error sources included. If You want the same from 10 to 35% flow, two dp transmitters could be used.

Processline Error -/Uncertainty calculation

```
Standard/Flowcalculationmethod 1/2/3?_____(S/1/2/3) 3
ERROR/UNCERTAINTYSOURCE            SIZE    IMPACT ON FLOW MEASURE UNCERTAINTY (%)
Flow (% of Maximal flow)_____      10   20   30   40   50   60   70   80   90   100
Standard uncertainty_____      0.5  0.5  0.5  0.5  0.5  0.5  0.5  0.5  0.5  0.5
Flow calculation mathematic Error____    0.08 -0.0 -0.0 -0.0 -0.0 -0.0 0.00 0.00 0.00  0.0
1.dp-transmitter % of maximal dp     0.1 4.99 1.26 0.55 0.31  0.2 0.13 0.10 0.07 0.06 0.04
dp-transmitter % of actual dp_____   0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
Throat diameter(mm)_____ 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
Tube diameter  (mm)_____    1 -0.1 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0
Tube roughness (mm)_____ 0.05  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
Density     (% act)_____  0.1 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04
Viscosity   (% act)_____    1 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Kappa       (% act)_____    1  0.0  0.0 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
3.Fluid Press.(% act)                  0.1 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
4.Fluid Temp      (C)                     1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1
Other ERRORS % actual flow_____   0    0    0    0    0    0    0    0    0    0
Other UNCERTAINTIES % actual flow_____    0    0    0    0    0    0    0    0    0    0
Total uncertainty % actual Flow_____     5,03 1,36 0,78 0,62 0,57 0,54 0,54 0,53 0,53 0,53
```

Table 3.4.1 Contributions from different uncertainties on the Total flow measurement uncertainty by 10, 20…100% flow.

But where do You put the square root calculation?
In the dp transmitter or in the receiving computer?
In general You can say (for 4-20 mA transmitters);
If You want to measure 50-100% flow, choose a linear dp-transmitter.
If You want to measure <50-100% flow (ex 10-100 %), choose
a dp-transmitter with square -root function.
Why?
This question is still being analyzed by Matematica and cannot be 100% answered here,
but it has to do with the signal flow in the transmitter and between transmitter
and computer. The rule above is general and based on mathematics but
every dp transmitter has to be analyzed individual to get an exact individual rule.
Get in touch with Matematica if You want an 100% answer.

3.4.2 Temperature and static pressure transmitter.

For gases density (dynamic viscosity and isentropic expansion factor)
varies with temperature and static pressure.
Since these physical properties has an impact on the k-factor in the
flow equation q=k*sqrt(dp), and because temperature and static pressure

varies along the tube and throat device, it's important to know where
static pressure and temperature of the gas should be measured to calculate
the correct physical properties.
According to the standard the pressure and temperature of the gas
should be measured or calculated in the center of the throat device
upstream or downstream pressure tapping cross section plane.
It's impossible to measure here because the standard will be violated and the flow will be
disturbed. Then You have to measure in another place, upstreams or downstrems
(temperature) or in the pressure tappings (pressure), and then calculate the temperature
and static pressure at the center of the upstream (or downstream) pressure tapping plane,
to be able to calculate a correct k-factor. Note; Even if temperature and static pressure are
stable upstreams or downstreams the device, they can vary with the flow in the upstream or
downstream pressure tapping plane, because You have a flow cross section area decrease,
specially for orifice plate with corner tappings. This results in a static pressure and
temperature decrease because of thermodynamic laws like energy conservation.
This decrease has to be under control and sometimes calculated/measured online
for big flowspeeds of gases, if You want to measure as good as possible.
Let's make a Processline calculation of the pressure and temperature
decrease at the upper pressure tapping for our case (se Table 3.4.2).
The orifice plate is then replaced with a abrupt diameter change of the tube from
300 mm to 175 mm.
The pressure and temperature decrease in the inlet plane of the pipe reduction is
a good estimation for the pressure and temperature decrease at the upper pressure tapping
of the orifice plate.
It means appr 0.6 kPa (=0.2 %) pressure - and 0.1 C temp-decrease at maxflow.
Since pressure can be measured in the upstreams pressure tapping, according to the
standard, only temperature decrease has to be taken into account
(=0.1C =0.1/(200C+273)%=0.02% of Kelvin temp).
If we use the ideal gas law the error of the density will also be 0.02%
Since only half the error of the density affects the k-factor (while massflow can be
calculated as k2*sqrt(density)*sqrt(dp)) it's negligible.
So: If we measure static pressure in the upstreams pressure tapping and
temperature 2 m upstreams (standard limt at least 1.5 m), it's good enough for our
demands.
Let's pick out transmitters with the uncertainties 0.1% of 300 kPa and 1C.
Then, according to Pos 3 and 4 in Table 3.4.1, the impact of these uncertainties
on the total flow measurement uncertainty is under control.

PROCESSLINE CALCULATION OF PRESSURELOSSES

```
                              INPUT
Processline:Pressurelosses/File: F:\p50\liptaktr.yck
Fluid:  Steam
Temperature?_____(C)    200
Absolute Pressure?_____(kPa)    300
Tubelength?_____(m)      2
Interior tubediameter cold (=20 C)?_____(mm)    300
```

```
Pipe roughness k?_____(mm)      0
Inlet-flow?_____(ton/h)   3
Adiabatic flow (=isolated tube) or Meidatemp>Environmenttemp
===============================RESISTANCES===============================
                    Nr_____1
        Resistancetype?_31.Abrupt reduced tubesize
            Resistance=_____0,36389
        (m) after Inlet?_____2
         Pressureloss %=_____0,0060386
               , mbar=_____0,18116
 New tubesize   (mm) ?_____175
```

OUTPUT

```
-----------------------TOTAL------------------------
Resistance_____= 0,46628
Pressurereduction (reversible+irreversible)__(kPa)= 0,56059
Pressurereduction_____(mbar)= 5,6059
Pressurereduction_____(% of inletpressure)= 0,18686
Pressureloss (irreversible)_____(kPa)= 0,023213
```
Outletpress. (bar)=2,9944_____(kPa)= 299,44
Outlettemperature_____(C)= 199,87
```
Outlet Flowspeed in tube at maxflow_____(m/s)= 24,859
-----------------------TUBE-------------------------
Resistance_____= 0,025597
Pressurereduction (reversible+irreversible)__(kPa)= 0,036842
Pressurereduction_____(mbar)= 0,36842
Pressurereduction_____(% of inletpressure)= 0,012281
_____PHYSICS REPORT (AT TUBE INLET)_____
Density_____(kg/m3)=  1,396
Dynamic viscosity_____(Pas*E-6)= 16,125
Reynolds number_____= 2,1933E5
```
Table 3.4.2 Static pressure and temperature decrease for example 1 .

3.5 Flow-calculation with the Matematica algorithm.

As mentioned; conventionally flow can be calculated as; flow=k*sqrt(dp).
However, this is an approximation of the standard algorithm that's
insufficient for many cases. In practice the mathematical error introduced with this method
can be as big as 10 % and more, specially for gases!
What's the mathematical error for our case?
Let's take a look at a Processline calculated mathematical report (Table 3.5);
As You can see the standard uncertainty is 0.5 % in average from 10-100 % flow
(= 0.3 to 3 ton/h).
But if You calculate the flow q = 3*sqrt(dp) You will get 1 % (see pos 2 in Table 3.5),
and that's not sufficient for our case.
Here comes the Matematica algorithm to eliminate this problem (see pos 3 in Table 3.5).
Flow = 3*sqrt(dp)*f(q)
where f(q)=(1-0.199052E-3*q*q)/0.998209*(1+0.84203E-2/q(3/4))/1.00369**
(according to pos 3 in the Processline computer calculated Table 3.5).
Note; The structure of this algorithm is general but the
numbers in the algorithm are optimized for every actual case.
As q (= 3*sqrt(dp)) is a function in the dp-transmitter, the flow calculation can be
improved in the receiving computer as; Flow:=q*f(q),
where q comes as 4-20 mA from the dp-transmitter and 20 mA = 3 ton/h for our example.
This new precise calculated flow has an average uncertainty of 0.51 % instead of 1 %.

The reduction of the calculation error can be much bigger for other cases (typical form 10 to 1 % in the site).

Processline computer calculated flow algorithms.
Average standard uncertainty btw. min- & max. flow__(%)=   0.5
1.Avg. standard unc. + math. error in q= 3.0069*sqrt(dp)_(%)= 0.88
(Used for best Precision at Normal flow=67%*Maximal flow)
2.Avg. standard unc. + math. error in q=   3*sqrt(dp)_(%)=   1
(Used for best Precision at Maximal flow)
3.Avg. standard unc. + math. error in q=   3*Sqrt(dp)*f()=   0.5
where f(dp)=(1-0.179146E-2*dp)/0.998209*(1+0.369391E-2/dp**(3/8))/1.00369
where f(q)=(1-0.199052E-3*q*q)/0.998209*(1+0.84203E-2/q**(3/4))/1.00369
(Where ** = raised to)
(Chose the function, f(dp) or f(q), thats most convenient)
(Used for best precision at all flows)
Table 3.5 SOME FLOWCALCULATION ALGORITHMS WITH UNCERTAINTIES
(See Fig. 3.5 for a graphical presentation).

Matematica algorithm;
Flow= 3*sqrt(dp)*f()

3.007 ton/h

3 ton/h

67%*max.flow

Calc method 1;
Flow=3.0069*sqrt(dp)

Calc.method 2;
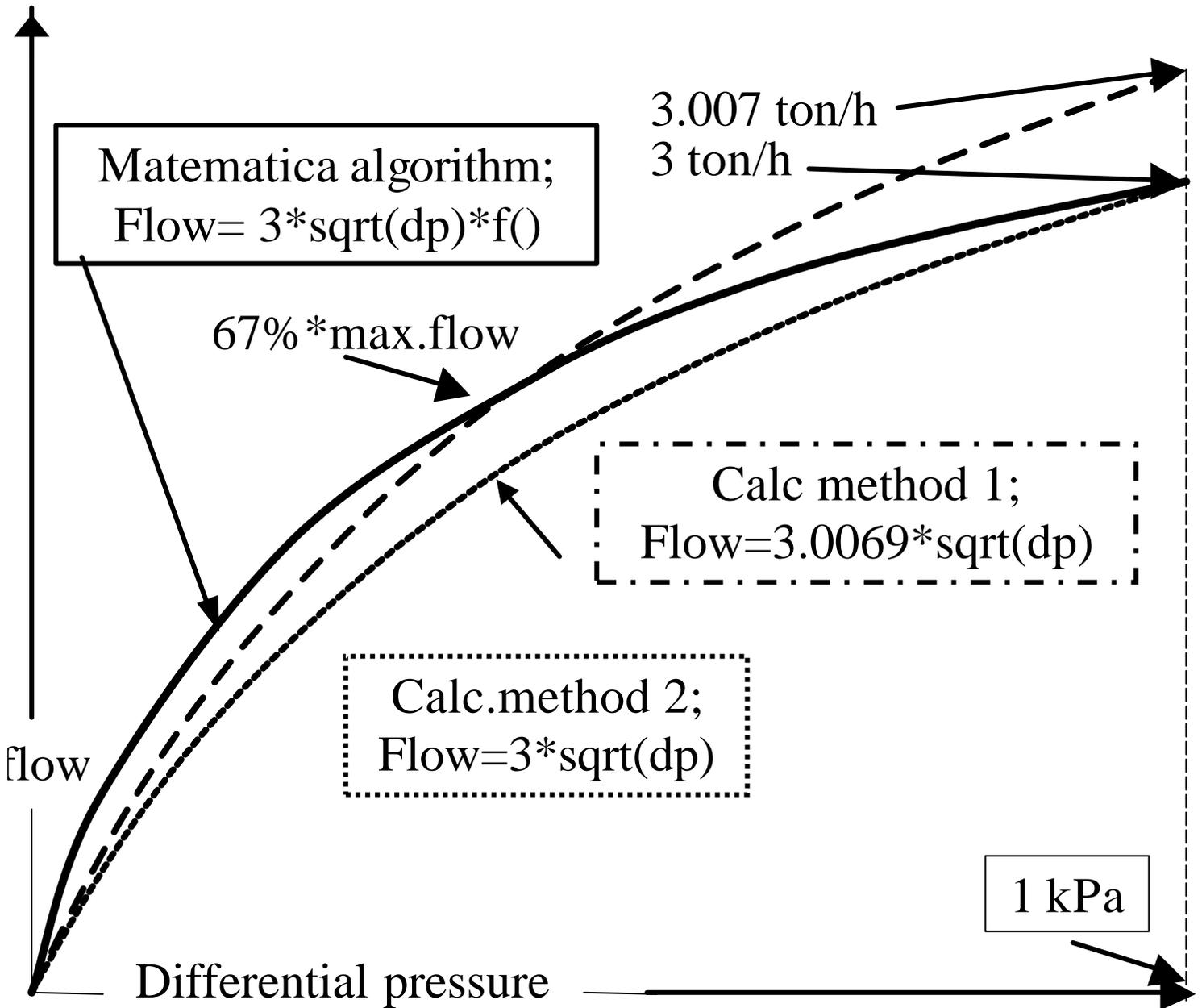Flow=3*sqrt(dp)

1 kPa

flow

Differential pressure

Fig. 3.5. Comparison of flow calculation algorithms
for example 1.

3.6 The Matematica-algorithm, background and function.

3.6.1 General considerations.
**The Matematica algorithm is close to 1 and can be seen as a complement
and not a substitute for the square root function.**

If You work with function blocks in Your computer system,
place the Matematica algorithm in a separate function block after
the square root function.
If You work with sequence programs like Pascal or C,
put the line with the Matematica algorithm after the sqrt function line.
In this way You can easily put the Matematica algorithm on and off,
if anything goes wrong, or You are looking for errors in Your software.
When the Matematica algorithm is = 1 it's not needed.
It's designed by analysis of the standard for orifice plates, but can be used
for all throat devices.
It's calculated and optimized for each flow-case by Processline computer software.
It consists of two parts, one for small flow speeds and the other for big flow speeds.
It has to do with the physical properties of the fluid.
At small flows the dynamic viscosity distorts the sqrt function and
(only for gases) at big flows the isentropic expansion factor (also called kappa)
distorts the sqrt function (see Fig. 3.5).

3.6.2 The Matematica algorithm at small flows.
At small flows, the second part of the algorithm comes into operation, it means;
(1+0.84203E-2/q**(3/4))/1.00369. (where **=raised to).
Where 1.00369 is a measure how big the impact is from this part of the algorithm.
When this number is 1 there is no impact (see Fig. 3.5).

3.6.3 The Matematica algorithm at big flows.
At big flows, the first part of the algorithm comes into operation;
(1-0.199052E-3*q*q)/0.998209
Where 0.998209 is a measure how big the impact is (1=no impact).
If one or booth parts of the algorithm is 1, one or booth parts are
not reported in the Processline computer calculated flow calculation-methods report, just
for simplification.
In the area between small and big flow booth or one or none of
the parts of the algorithm can be in operation (see Fig. 3.5).
Note; The numbers in the algorithm is optimized for each flow meter
and cannot be used for other flow meters.

3.7 The demand (0.7 % of actual flow) is accomplished.
At last, let's see if we can meet our demands with 0.7 % uncertainty of actual flow
from 10 to 100 % flow. Let's make a Processline Error/Uncertainty calculation of Our flow
meter (see table 3.7a).

Comment;
In this calculation the best possible values for uncertainty/error-sources are used.
As You can see, the total uncertainty is well below 0.7 % between 30 and 100 % flow.
Below 30 % flow we need;

1. one more dp-transmitter, with 0.7% accuracy in % of span
2. or a dp-transmitter with 4-20 mA that can be rescaled online,

3. or a dp-transmitter with a digital output ,like the Hart protocol.

For simplicity, let's make an Error/Uncertainty calculation for the small range dp-transmitter, it means 0-33.33...% flow (20mA =1 ton/h for our example). The result is reported in table 3.7b.

Result;
With the Matematica approach concerning;

1. **Design.**
2. **Manufacturing.**
3. **Installation in tube.**
4. **Instrumentation.**
5. **Calculation of the flow with the square root function improved with the Matematica algorithm.**

0.7 % accuracy of <u>actual</u> flow from 10 (=0.3 ton/h=30%*1 ton/h) to 100 % flow is possible, according to the goal.
Remember that booth flow signals (0-33.33... % and 0-100 %) must booth be calculated in the dp-transmitter(s) as q = 3*sqrt(dp).
When the 4-20 mA signal(s) is sent to a computer for adjustment with the Matematica algorithm, You also need some switching logic to switch between the two signals (if You have two signals).
The flow signal from the dp-transmitter(s) can also be sent to the computer digitally, for example with the Hart protocol.
Then often one dp-transmitter is enough.
As the digital world is complicated, I recommend the Hart-protocol, because it's a complement to the 4-20 mA signal, It means You can go back to the analog world (4-20 mA) if You get problems. This is a big advantage.

Processline Error -/Uncertainty calculation 0.3-3 ton/h.

```
Standard/Flowcalculationmethod 1/2/3?_____(S/1/2/3) 3
ERROR/UNCERTAINTYSOURCE             SIZE    IMPACT ON FLOW MEASURE UNCERTAINTY (%)
Flow (% of Maximal flow)_____     10   20   30   40   50   60   70   80   90   100
Standard uncertainty_____       0.5  0.5  0.5  0.5  0.5  0.5  0.5  0.5  0.5  0.5
Flow calculation mathematic Error____    0.08 -0.0 -0.0 -0.0 -0.0 -0.0 0.00 0.00 0.00  0.0
1.dp-transmitter % of maximal dp      0.1 4.99 1.26 0.55 0.31  0.2 0.13 0.10 0.07 0.06 0.04
dp-transmitter % of actual dp_____    0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
Throat diameter(mm)_____ 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
Tube diameter  (mm)_____    1 -0.1 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0
Tube roughness (mm)_____ 0.05  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
```

```
Density      (% act)_____  0.1 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04
Viscosity    (% act)_____    1 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Kappa        (% act)_____    1  0.0  0.0 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
3.Fluid Press.(% act)_____   0.1 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
4.Fluid Temp    (C)                       1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1 -0.1
Other ERRORS % actual flow_____       0    0    0    0    0    0    0    0    0    0
Other UNCERTAINTIES % actual flow_____       0    0    0    0    0    0    0    0    0    0
Total uncertainty % actual Flow_____       5,03 1,36 0,78 0,62 0,57 0,54 0,54 0,53 0,53 0,53
```
Table 3.7a Best possible Total flow measurement uncertainty for Example 1

Processline Error-/Uncertainty calculation 0.3-1 ton/h.

```
Error-/Uncertainty calculation
Standard/Flowcalculationmethod 1/2/3?_____(S/1/2/3) 3
ERROR/UNCERTAINTYSOURCE         SIZE       IMPACT ON FLOW MEASURE UNCERTAINTY (%)
Flow (% of Maximal flow)_____      30,0 37,8 45,6 53,3 61,1 68,9 76,7 84,4 92,2  100
Standard uncertainty_____     0,50 0,50 0,50 0,50 0,50 0,50 0,50 0,50 0,50 0,50
Flow calculation error_____       0,06 0,03 0,01 0,00 -0,0 -0,0 -0,0 -0,0 -0,0 0,00
dp-transmitter % of maxdp_____ 0,07 0,39 0,25 0,17 0,12 0,09 0,07 0,06 0,05 0,04 0,03
dp-transmitter % of act. dp_____ 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Throat diameter (mm)_____ 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01
Tube diameter   (mm)_____ 1,00 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1
Tube roughness  (mm)_____ 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Density      (% act)_____ 0,10 0,05 0,05 0,05 0,05 0,05 0,05 0,05 0,05 0,05 0,05
Viscosity    (% act)_____ 1,00 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01 0,01
Kappa        (% act)_____ 1,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Fluid,Press.(% act)_____ 0,10 0,05 0,05 0,05 0,05 0,05 0,05 0,05 0,05 0,05 0,05
Fluid,Temp      (C)_____ 1,00 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1 -0,1
Other ERRORS % actual Flow_____      0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Other UNCERTAINTIES % actual Flow____      0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Total uncertainty % actual Flow            0,70 0,61 0,56 0,54 0,54 0,54 0,54 0,53 0,53 0,53
```
Table 3.7b Best possible Total flow measurement uncertainty for Example 1 (0.3-1 ton/h).

3.8 Improvement of an old, already installed, throat-device by identification and reduction of error/uncertainy-sources.

The calculations we have seen so far are on an optimized design,
with no restriction on tubesize, differential pressure and more.
But already installed flow meters cannot be optimized afterwards that easy.
Can we analyze and improve these afterwards?
Yes, we can.
With a computer error/Uncertainty-calculation we can identify the error-sources

and, for example, eliminate the mathematical error in the sqrt function with the Matematica algorithm.

No new equipment has to be installed.

Just key in the Matematica algorithm after the sqrt function in Your computer and the flow calculation error can be reduced from 10 % to 0 %.

Note; The sqrt-function produces an error and not an uncertainty!

Or You can move the sqrt function from/to the dp-transmitter.

Or You can do a Pressure/Temperature density compensation.

The weakest part of the chain can be identified with a Error/Uncertainty computer calculation.

Note; There are no thumb-rules, each case must be analyzed individual.

Let's get concrete and take a look of a typical old installation (example 2).

Example 2 (= example 1 but a smaller tube and throat);

Fluid	**Steam at 200C, 300 kPa absolute**
Flow	**0.3-3 ton/h**
Tube size	**100 mm**
Throat size	**65 mm**
Throat device	**Orifice plate (corner tappings)**
Differential pressure at maxflow	**57.71 kPa**

Let's take a look on the Processline calculated algorithm report for this example (table 3.8a); If the flow is calculated in the traditional way (se pos 2, table 3.8a);

Flow:=0.3949*sqrt(dp), the calculation error + standard uncertainty = 5.3 % (average value from 10-100 %).

If all other uncertainties are as small as possible, the total flow-calculation uncertainty will be as below in the Error/Uncertainty Processline calculated matrix (see Table 3.8b).

This means an average total uncertainty of 5.7 % of _actual_ flow, from 10 to 100% flow.

Now we want to reduce this number mathenatical.

In table 3.8b we can identify the Flow calculation mathematical error as the main error source.

Therefor;

Let's use the Matematica algorithm on this example (se pos 3 in table 3.8a);

From the dp-transmitter we get q:=0.3949*sqrt(dp)

Then, in the connected computer, we calculate flow:=q*f(q).

Now the calculation error + standard uncertainty will be 0.7% of _actual_ flow (average value from 10-100 %).

If all other uncertainties are as small as possible, the total flow-calculation uncertainty will be as in the Error/Uncertianty Processline calculated matrix (Table 3.8c).

It means an average total uncertainty of 1.4 %, a big improvement.

The only thing You have to do is to key in the Matematica algorithm in Your computer, and You will reduce the average flow measurement uncertainty From 5.7 to 1.4 % of _actual_ flow, for this example.

No new hardware has to be installed or changed.
It means that even bad designed throat devices, or big changes in the tube,
like increasing flow, often can be dramatically improved with the Matematica algorithm.

Average standard uncertainty btw. min- & max. flow__(%)=   0.7
1.Avg. standard unc. + math. error in q=0.412836*sqrt(dp)_(%)= 2.9
(Used for best Precision at Normal flow=67%*Maximal flow)
2.Avg. standard unc. + math. error in q= 0.3949*sqrt(dp)_(%)=   5.3
(Used for best Precision at Maximal flow)
3.Avg. standard unc. + math. error in q= 0.3949*Sqrt(dp)*f()=   0.7
where f(dp)=(1-0.121333E-2*dp)/0.929976*(1+0.0119736/dp**(3/8))/1.00262
where f(q)=(1-0.778044E-2*q*q)/0.929976*(1+0.596475E-2/q**(3/4))/1.00262
(Where ** = raised to)
(Chose the function, f(dp) or f(q), thats most convenient)
(Used for best Precision at all flows)
Table 3.8a SOME FLOWCALCULATIONALGORITHMS WITH UNCERTAINTIES

Processsline Error -/Uncertainty calculation

Standard/Flowcalculationmethod 1/2/3?_____(S/1/2/3) 2

ERROR/UNCERTAINTYSOURCE	SIZE	IMPACT ON FLOWMEASUREUNCERTAINTY (%)									
Flow (% of Maximal flow)_____		10,0	20,0	30,0	40,0	50,0	60,0	70,0	80,0	90,0	100
Standard uncertainty_____		0,58	0,58	0,59	0,59	0,61	0,63	0,68	0,75	0,84	0,97
Flow calculation mathematical error _		*-8,0*	*-7,4*	*-6,9*	*-6,4*	*-5,7*	*-5,0*	*-4,1*	*-3,0*	*-1,6*	*0,00*
dp-transmitter % of maxdp_____	0,10	5,69	1,43	0,63	0,35	0,22	0,15	0,10	0,08	0,06	0,04
dp-transmitter % of act. dp_____	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Throat diameter (mm)_____	0,01	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Tube diameter (mm)_____	1,00	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4
Tube roughness (mm)_____	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Density (% act)_____	0,10	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Viscosity (% act)_____	1,00	0,01	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Kappa (% act)_____	1,00	0,00	0,00	0,01	0,01	0,02	0,02	0,03	0,04	0,06	0,07
Fluid,Press.(% act)_____	0,10	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Fluid,Temp (C)_____	1,00	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
Other ERRORS % actual Flow_____		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Other UNCERTAINTIES % actual Flow____		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total uncertainty % actual Flow		*10,3*	*8,12*	*7,52*	*6,97*	*6,35*	*5,62*	*4,75*	*3,72*	*2,49*	*1,04*

Table 3.8b Total flow measurement uncertainty for Example 2 without the Matematica algorithm.

Processsline Error -/Uncertainty calculation

Standard/Flowcalculationmethod 1/2/3?_____(S/1/2/3) 3

ERROR/UNCERTAINTYSOURCE	SIZE	IMPACT ON FLOWMEASUREUNCERTAINTY (%)									
Flow (% of Maximal flow)_____		10,0	20,0	30,0	40,0	50,0	60,0	70,0	80,0	90,0	100
Standard uncertainty_____		0,58	0,58	0,59	0,59	0,61	0,63	0,68	0,75	0,84	0,97
Flow calculation mathematical error _		*0,11*	*0,00*	*-0,0*	*-0,0*	*-0,0*	*0,00*	*0,00*	*0,01*	*0,00*	*0,00*
dp-transmitter % of maxdp_____	0,10	5,69	1,43	0,63	0,35	0,22	0,15	0,10	0,08	0,06	0,04
dp-transmitter % of act. dp_____	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Throatdiameter (mm)_____	0,01	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Tubediameter (mm)_____	1,00	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4
Tuberoughness (mm)_____	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Density (% act)_____	0,10	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Viscosity (% act)_____	1,00	0,01	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Kappa (% act)_____	1,00	0,00	0,00	0,01	0,01	0,02	0,02	0,03	0,04	0,06	0,07
Fluid,Press.(% act)_____	0,10	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Fluid,Temp (C)_____	1,00	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1

```
Other ERRORS % actual Flow_____      0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Other UNCERTAINTIES % actual Flow____      0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00 0,00
Total uncertainty % actual Flow_____     5,75 1,60 0,97 0,81 0,77 0,77 0,80 0,85 0,93 1,04
```
Table 3.8c Total flow measurement uncertainty for Example 2 with the Matematica algorithm.

3.9 Other big errorsources, from my experience as a flow measure consultant.

This chapter shall be seen as a warning list for common design errors for throat devices.
It is not a complete design instruction, but will point out some values and
units that must be under control, before You can start to improve a new or old flow meter.
Before You can do that You have to know every value and unit that has an impact
on the constant k in the relation flow=k*sqrt(dp).
At least 14 numbers and units are involved, as pipe roughness, tube size and throat size,
and every number and unit has to be correct with as small uncertainty as possible.
Also, if several people are involved, You have to mean the same thing with the units.
Here comes some big errorsources, according to my experience.

3.9.1 Flow unit Nm3/h

This is the biggest error-source.
Note; This is a mass flow unit,
where the relation between kg/h and Nm3/h is;
q(kg/h)=density(kg/m3 at normal conditions)*q(Nm3/h).
This unit is often used for chemical processes (instead of kmol/h)
and often varies from country to country depending on the local climate.
When this unit is used it should be connected with the density
of the Fluid at normal conditions and the actual definition of normal conditions,
(for example in Sweden 0C, 1.01325 BarA).
Another problem with this unit, when it's used instead of kmol/h,
is an introduction of an error, because it's only precise for ideal gases,
which is never the case in reality.
When You want to mix two or more gases/liguids for a chemical process, like combustion,
use kmol/h (/sec/min) instead for elimination of this error.
For power measurement/calculation use ton (kg)/h (min/sec) instead.
Advise; Don't use Nm3/h (or other Normalvolumes) if You don't have to.
Also, don't use m3/h (or other volumes/time unit), because they are often
taken for Normalvolume/time unit (like Nm3/h).
Try to use mass flow/time-units in the first place, like kg, ton, kmol/h,min,sec.

3.9.2 Static pressure units.

When You calculate the k-factor, the units have to be correct.
For example, is the static pressure unit over pressure (like BarO)
or absolute pressure (like BarA).
Always make this clear when You calculate the physical properties of the fluid.
Use absolute pressure if possible.

3.9.3 Pipe roughness.

An important factor, specially for small pipes.

Pipe roughness affects the flow cross section profile and can influence the flow measurement with several percents.
If You adjust the k-factor for pipe roughness according to german VDI/VDE standards, the error contribution can be eliminated.

3.9.4 Unsharp edge of an orifice plate.

Threw dust and pollution of the Fluid, the edge of the orifice plate can be rounded with time. This can introduce a flow measurement error of 5 % and more, but can be compensated for according to VDI/VDE.
If You have this kind of problems, You can make the edge round from start, to avoid changes with time. But don't forget to compensate for the round edge when You calculate the k-factor.

Bibliography; ISO 5167-1
    Reference number ISO 5167-1:1991(E).
    ISO 5167-1 Amendment 1.
    Reference number ISO 5167-1:1991/Amd 1:1998(E).
    VDI/VDE 2040 & 2041
    PROCESSLINE, computer software, copyright (c) 1987, 2003
    Stephan Rudbäck, Matematica.