Szent István University

ANALYSIS OF THE PARAMETERS OF AN ENVIRONMENTALLY FRIENDLY COMMUNAL SEWERAGE SYSTEM

Theses of Ph.D. Dissertation

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NOTATION AND ABBREVIATIONS

Sign	Name	Dimension
PE	People Equivalent	
EPA	Environmental Protection Agency	
HDPE	High Density Polyethylene	
TR	Thermodynamic System	
PLC	Programmable Logic Controller	
A	surface	m^2
$\underline{A}$	matrix	-
a	sound velocity	m/s
$\underline{b}$	column vector of disturbing parts	-
c	height of a big lift formed by two lifts connected by a counter fall or a horizontal pipe section	m
c_p	specific heat at constant pressure	J/(kg·K)
c_v	specific heat at constant volume	J/(kg·K)
D	determinant of matrix	-
d	diameter	m
e	distance of parallel pipe sections in a lift	m
f	specific energy demand referring to a m^3 of water	kWh/m^3
g	specific gravity	$9,81\ m/s^2$
H	enthalpy	J
h	specific enthalpy	J/kg
k	overall heat transfer coefficient	$W/(m^2 \cdot K)$
K	height of a counter fall pipe section	m
m	mass	kg
m’	number of counter fall pipe sections standing alone or connected to a lift causing static vacuum loss	-
l	length	m
L	number of counter fall pipe sections not connected to lifts causing static vacuum loss	-
n	number of closed lifts	-
p	pressure	Pa or bar abs.
q_v	vacuum pump volumetric flow rate	m^3/h
q_m	vacuum pump mass flow rate	kg/h
R^2	square of the correlation coefficient	-
r	air / water ratio	m^3/m^3
Q	heat	J
Q'_{max}	sewage peak flow	m^3/h
T	temperature	K
t	time	s or h
U	inner energy	J
u	specific inner energy	J/kg
V	volume	m^3
v	velocity	m/s
v’	fall of a pipe sections between two lifts	m
W	work	J
x	location coordinate measured at the center line of a pipe	-
x’	sewage height in a lift causing static vacuum loss	m

z	number of big lifts formed by two lifts connected by a counter fall or a horizontal pipe section	-
α	heat transfer coefficient	$W/(m^2 \cdot K)$
α'	angle of a pipe section	-
δ	wall thickness	m
κ	isentropic exponent	-
λ'	thermal conductivity	$W/(m \cdot K)$
λ	pipe friction coefficient	-
ρ	density	kg/m^3

indexes

P, Q, R, M	refers to interpolation points
i	refers to pipe section
j	refers to location
k	refers to time

1. ANTECEDENTS AND AIMS OF THE WORK

A large part of our Hungary is flat having high ground water table levels, conditions that make traditional gravity sewer systems difficult and expensive to install and operate. Laid in shallow trenches, vacuum sewerage systems offer an excellent alternative for these areas.

The first vacuum sewerage system was built in the Netherlands in the 1860's. As far as Hungary is concerned the first one was built in 1986 in Szentendre. Since then more than 50 modern, environmentally friendly vacuum sewerage systems have been operating in Hungary serving altogether more than 200.000 inhabitants.

Vacuum sewerage needs complex technical skills and knowledge (including public health, environment protection, hydromechanics, hydro machinery, civil engineering, principles of electricity, informatics and vacuum technics) that all form a complicated system having lots of parameters, yet it also has to be an economical solution. Certain questions of this special field regarding sizing and operation are not worked out thoroughly enough in principle or mostly treated based on the different experiences of the innovative predecessors often lacking solid theoretical background. The complexity of this field is probably the cause for the low number of scientific publications. In my dissertation firstly I summarized the technical history and technology of vacuum sewerage. I carried out researches on the hydrostatics of vacuum sewerage systems, their evacuation time and their energy demand for collecting a unit of fluid volume based on theory as well as experimenting on a vacuum sewerage pilot plant test rig designed and built by me.

1.1 The Hydrostatics of Vacuum Sewerage Systems

The pipelines of vacuum fluid conveying systems have a unique, so called saw tooth profile. The fall of the pipe has to be a minimum of two ‰ in direction of the vacuum station and so called lifts* are to be applied at certain distances. The pressure along the vacuum pipe in the presence of two phases (water and air) varies with location even in a constant still state (when the velocity of any phase in the system equals zero). With regard to the duty and safety of operation of vacuum sewerage systems it is essential to know the pressure as a function of location. The professional literature deems the static vacuum loss of a lift proportional with the difference of the height of the lift and the pipe diameter. This determination is not accurate enough. Moreover certain profile sections and their possible combinations (such as counter fall pipes) which appear sometimes in the practice having an effect on the pressure along the pipeline are not taken into account. This part of my researches focused on determining the static (so still steady state) vacuum loss on one lift and on different possible profile sections and their combinations enabling the determination of the maximum static vacuum loss (hundred percently filled up normal state) along the entire pipeline.

1.2 The Pump Down of Vacuum Sewerage Systems

The operation of every vacuum material conveying system starts with the evacuation process. The professional literature dealing with this field suggests the application of the so called pump down equation of concentrated parameters valid for vessel shaped volumes for determining the evacuation time of vacuum sewerage systems not taking into account the unique shape of such systems consisting of a relatively small vessel and mostly long pipelines.

Vacuum stations are not uncommon having as long as four km long individual pipe(s) connected to the sewage collection tank. There are vacuum systems in Hungary too that have all in all more than 40 km pipeline network and longer than four km vacuum mains. The modeling of the evacuation process of volumes of such a unique shape with concentrated parameters contains exaggerated simplifications from a scientific as well as a technical point of view, thus the accordingly calculated

* a lift consists of two 45 degree pipe sections causing an elevation (usually 300 mm) in the profile of the pipeline

evacuation time of large pipeline networks leads to a much shorter time than what it takes in reality. The vacuum pump sizing based on the above mentioned method can result in operational anomalies (such as the too frequent turning on and off of the vacuum pump causing increased energy consumption and a higher likelihood of motor burn down). Therefore scientific research in this field is not only timely but is also of practical importance. According to my hypothesis and measurement results the pump down process and time greatly depends on the shape of the volume to be evacuated.

1.3 The Specific Energy Demand of Vacuum Sewerage

The specific energy demand of vacuum sewerage is the most important parameter of the field on a long term. The number of professional articles related to this question is very low. The European Standard (MSZ EN 1091:2001) determines a wide range: 0.2 – 1 kWh/m^3.
Numerous factors influence the energy consumption of vacuum sewerage, two things of which are the most important: the ratio of the transporting air and the transported sewage (air/water ratio); the vacuum level kept in the central vacuum station. There is practically no hint regarding these questions in the professional literature, therefore it is not surprising that the operating staff does not know the optimal air/water settings either.

I found it worthwhile on one hand to experimentally test the effect of both the air/water ratio and the pressure level kept in the vacuum vessel on the static vacuum loss and the specific energy demand as well, on the other hand to determine the optimal operational settings.
To be able to research these relationships, I designed a vacuum sewerage pilot plant made of transparent acrylic pipes that well models real communal conditions. On this test rig all the relevant parameters can be adjusted and measured at the same time and the phenomena can be documented and visually followed as well.

It is important to note that the solid particle content of communal wastewater is seldom more than one percent, thus the sewage was deemed water during my researches as it is commonly accepted in the professional literature.

1.4 The Aims of the Work

The determination of the hydrostatic relations depending on the profile of a vacuum pipeline:
-the determination of the static vacuum loss of a closed and an open lift in the presence of two phases (water and air) in a still steady state;
-taking stock of the incorrectly designed or executed pipe sections (counter fall, horizontal or incorrectly designed or built pipe sections) and the determination of the static vacuum loss caused by them and the determination of the total static vacuum loss (hundred percently filled up normal state) of a vacuum pipe having such faulty sections in the presence of two phases (water and air) in a still steady state.

The examination of the evacuation of a vacuum system that consists of a vacuum pump, a vacuum vessel and a pipe (network):
-the modeling of the pump down process of vacuum sewerage systems with concentrated parameters;
-the modeling of the evacuation process of vacuum fluid conveying systems with divided parameters;
    -the application of the equations characterizing the non-adiabatic, unsteady flow of a compressible agent (air) in a pipeline;
    -for the solution of these equations the determination of the boundary conditions and the application of the method of characteristics;

-the application of the interpolated grid method and the creation of the necessary conditions (relations, initial and boundary conditions) for the establishment of a software capable of calculating the pump down process of a pipeline and possibly making a software;

-the completion of evacuation time measurements on communal vacuum sewerage systems in the presence of one phase (air).

The experimental determination of the specific energy demand of vacuum fluid conveying and the description of the explored relations:

-the design and establishment of a vacuum sewerage system experimental test rig well modeling the operation of real communal systems and on that the completion of a series of measurements at various air/water ratio and vacuum vessel pressure settings regarding the:

-total static vacuum loss of a pipeline and the comparison with the theory;

-specific energy demand of vacuum fluid conveying;

-the reliable and energetically optimal domain of operation of vacuum sewerage systems.

Based on the research results regarding the hydrostatics (and energy consumption) the establishment of a software capable of designing optimal longitudinal vacuum main profiles.

With the help of the software the design of the vacuum main profiles of the largest vacuum sewerage system in the world currently being built (Sultanate of Oman, Seeb project).

2. ANALYSIS OF THE PARAMETERS OF VACUUM SEWERAGE SYSTEMS

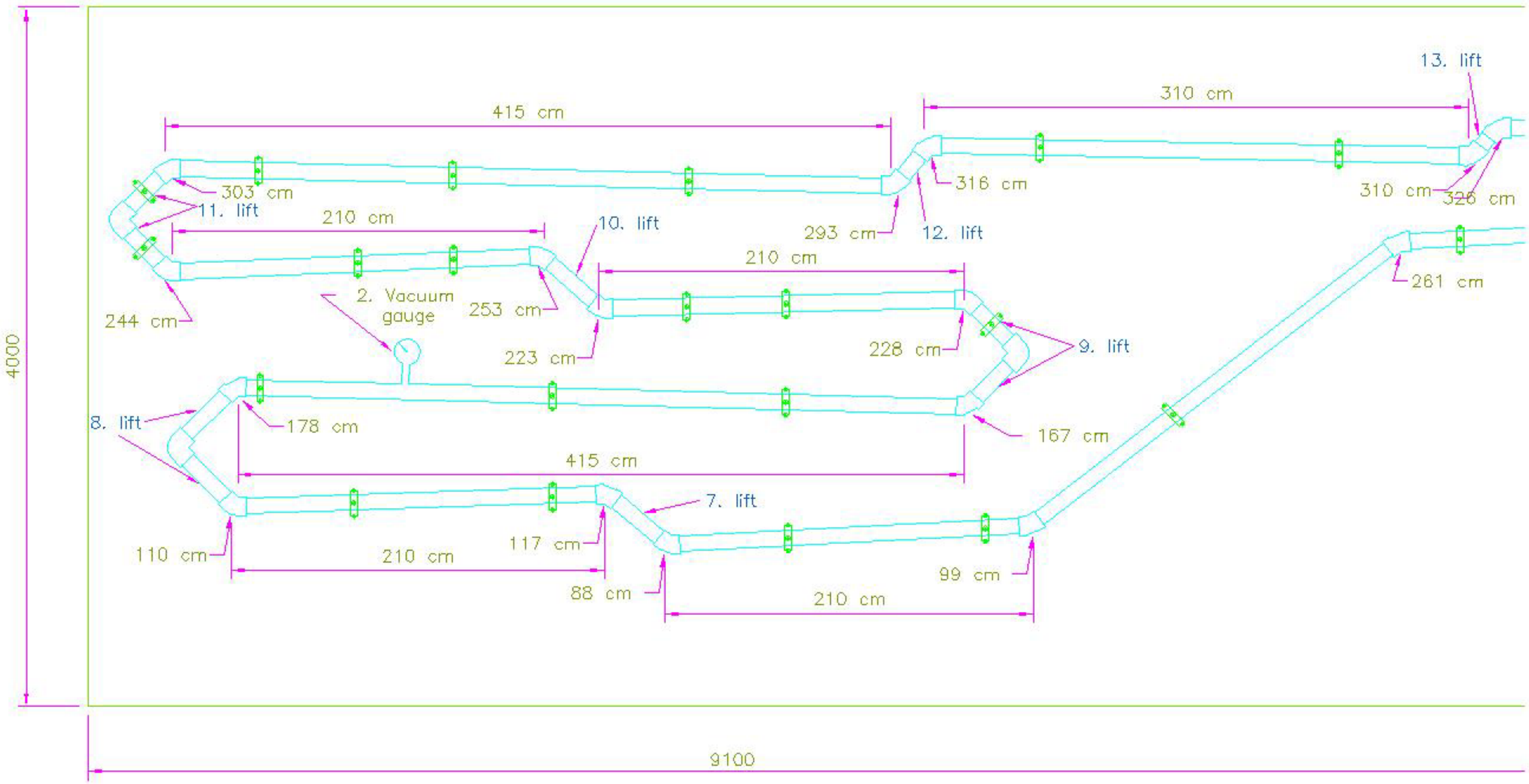
I had the opportunity to design and build an experimental vacuum fluid conveying system – well modeling realistic communal relations – at the premises of the Technical University of Timisoara. This enabled me to carry out measurements regarding the specific energy demand and the hydrostatics of vacuum sewerage systems at different air/water and vacuum vessel pressure settings on the vacuum sewerage pilot plant.

2.1 The Experimental Test Rig

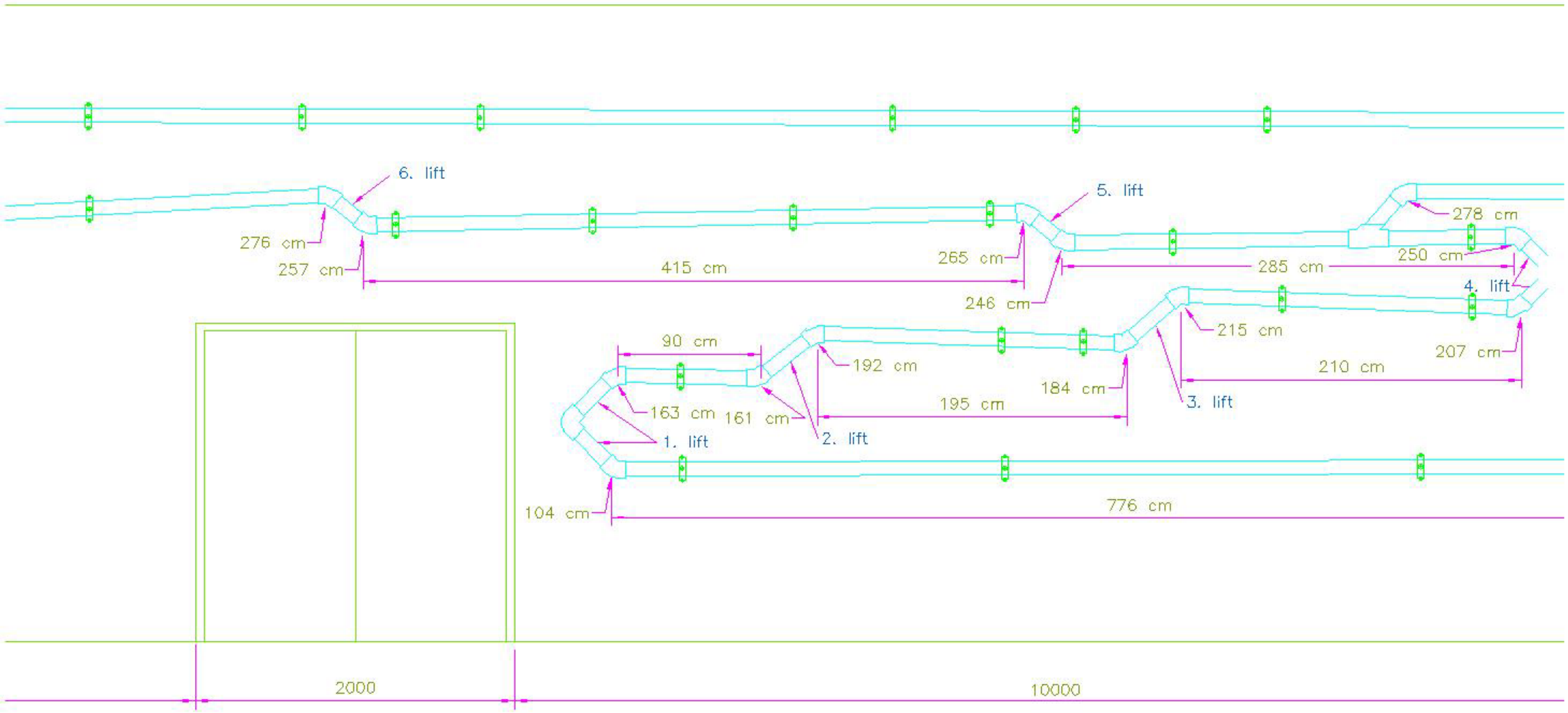
1. picture: The experimental vacuum fluid conveying test rig

The test rig consists of 88 m DN 90 mm transparent vacuum pipes, 2 units of SW Umwelttechnik type concrete collection chambers with 2 pieces of 90 mm diameter automatic Iseki vacuum interface valves and a 1.5 m^3 vacuum vessel.

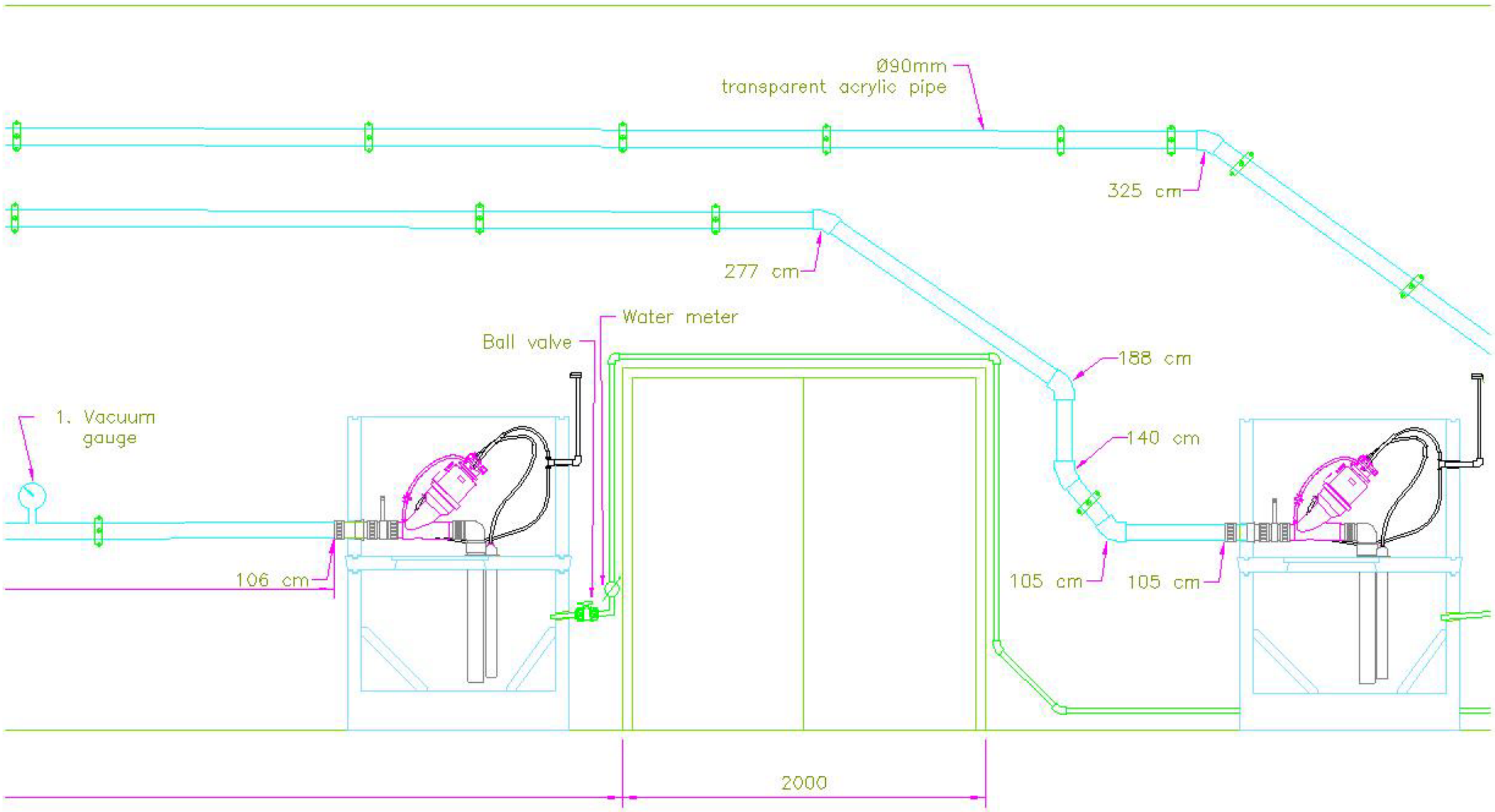
2. picture: The vacuum station of the test rig with a NASH vacuum pump, a separator tank with a gas flow meter, a variable frequency drive and a kW meter



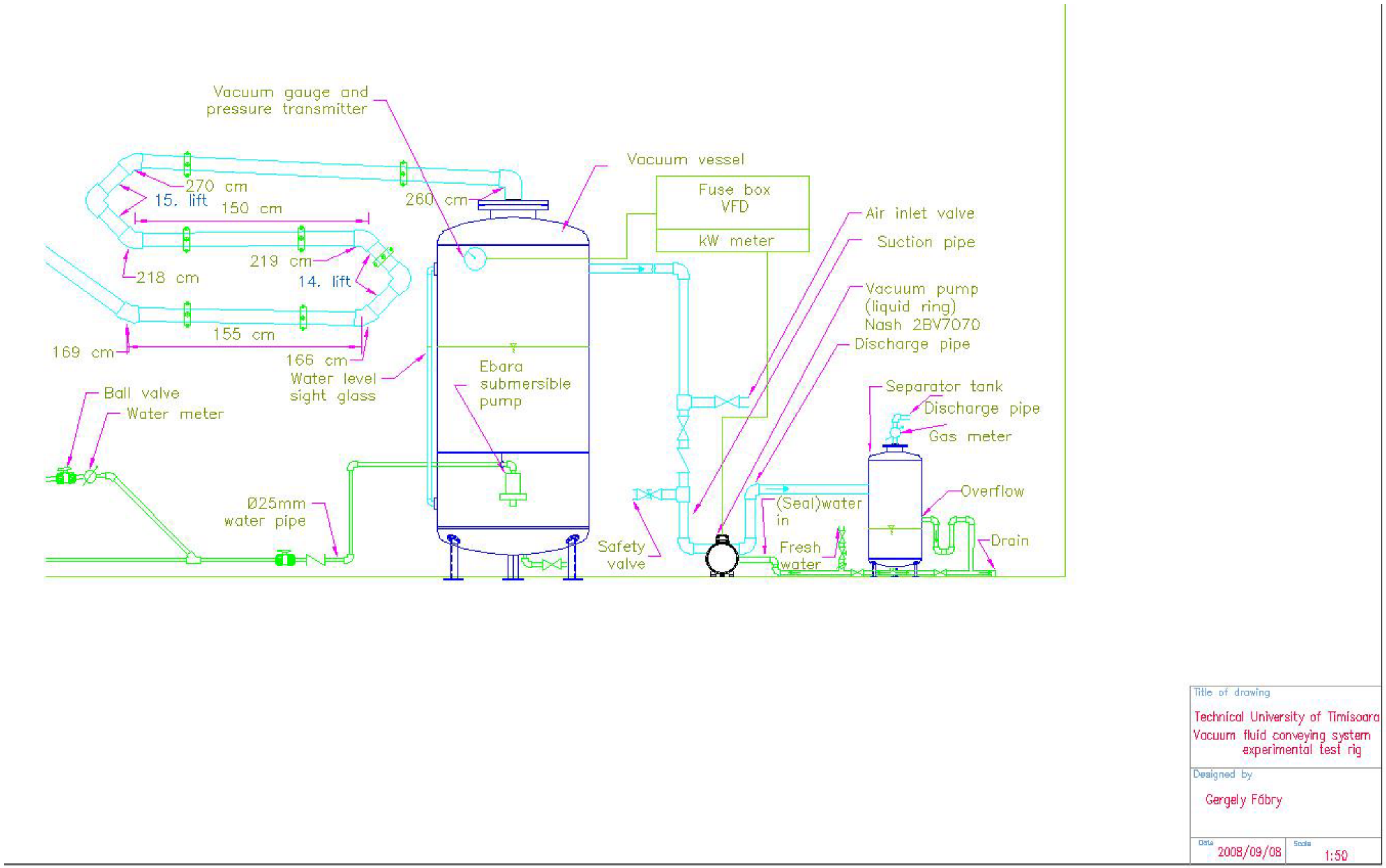
3. picture: The vacuum fluid conveying experimental test rig 1/4



4. picture: The vacuum fluid conveying experimental test rig 2/4



5. picture: The vacuum fluid conveying experimental test rig 3/4

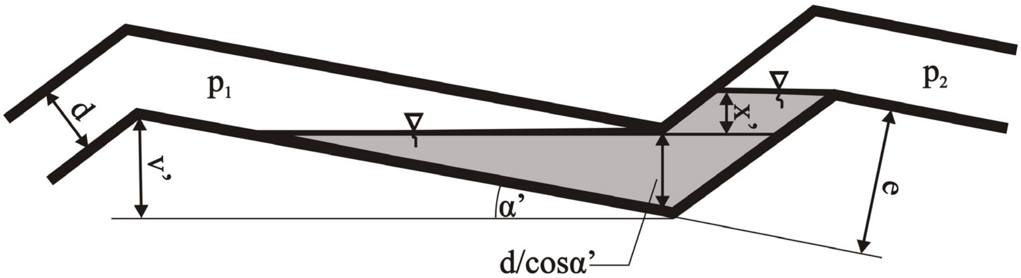


6. picture: The vacuum fluid conveying experimental test rig 4/4

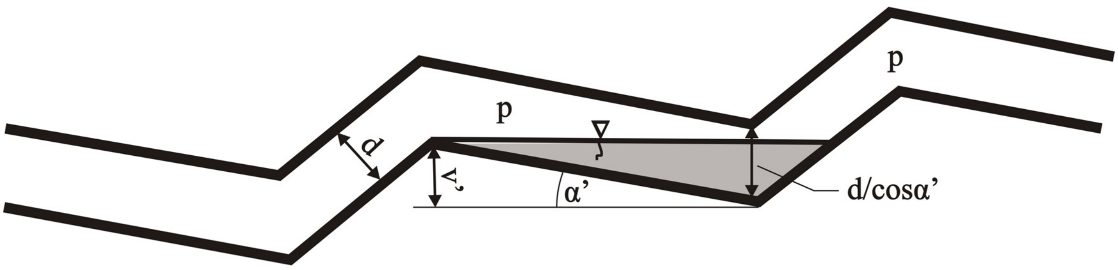
The vacuum is generated by a 2.4 kW NASH 2BV7070 type liquid ring vacuum pump with a suction capacity of 75 m^3/h. The vacuum pump can either be run at 50 Hz or with the help of the Danfoss variable frequency drive a preset pressure can be kept in the vacuum vessel.
The circulation of the colored water (substituting sewage) back to the collection chambers is maintained by a 0.2 kW Ebara submersible pump.

2.2 The Static Vacuum Loss of Vacuum Sewerage Systems

The proper operation of vacuum sewerage systems basically consists of the systematic transport of sewage plugs from the lifts, their regular regeneration and the assuring of sufficient pressure difference for moving them. Static vacuum loss can only be measured when there is no fluid transport in the pipelines, so when the velocity of any agent in the system equals zero, the necessary condition of which is the closed state of the vacuum interface valves. The total static vacuum loss can be defined as the pressure difference between the pressure of the collection tank in the vacuum station and that of the pipe section in front of the farthest valve chamber of each of the vacuum mains.

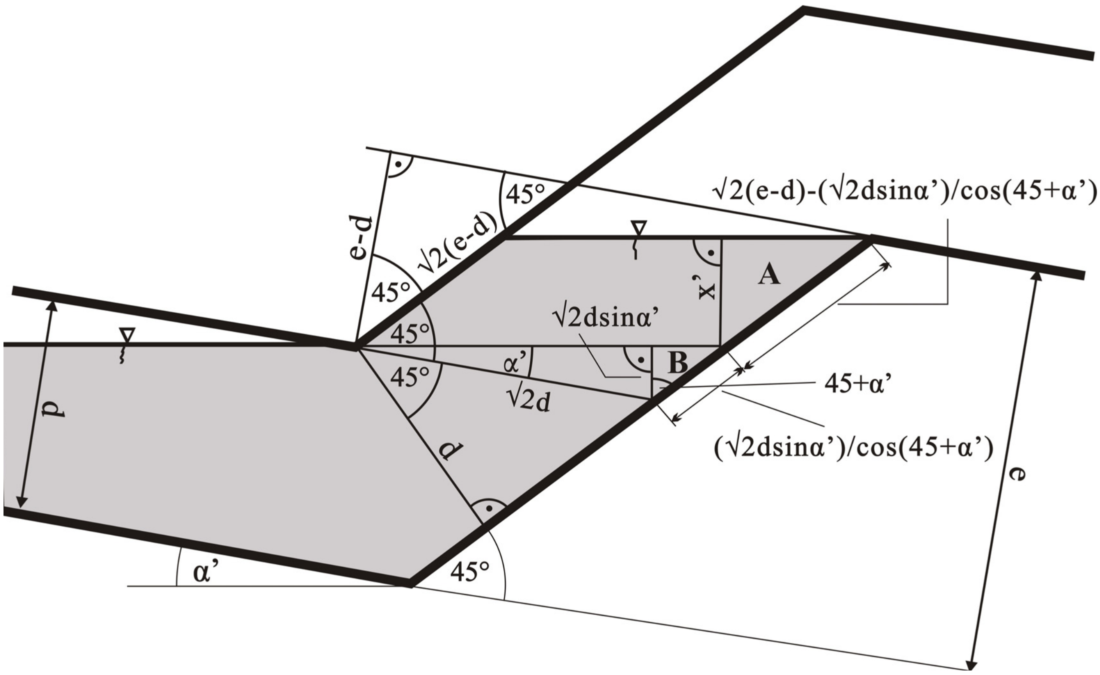


7. picture: Geometry of a closed lift and a sewage plug in it



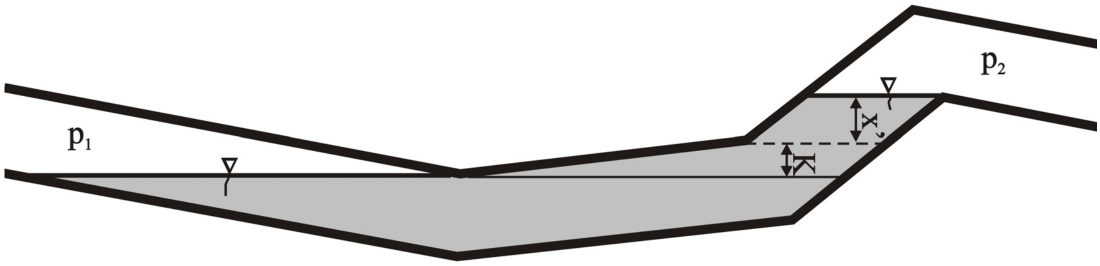
8. picture: Geometry of an open lift and a sewage plug in it

For the calculation of the total static vacuum loss of vacuum sewerage systems it is necessary to know first of all how much the loss is on one closed lift (9. picture). When determining the total static vacuum loss I assume that the water levels in all the lifts and counter falls are such that they cause maximal pressure loss, because the worst normal operating conditions need to be taken into account when sizing the system. This is called hundred percently filled up normal state (and I would like to emphasize that it is to be distinguished from the fully waterlogged state of operation which is to be avoided).

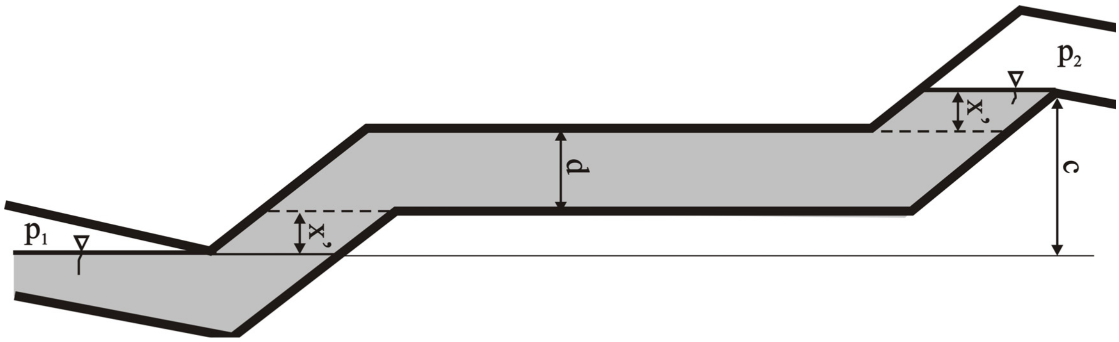


9. picture: A sewage plug in a closed lift causing maximal static vacuum loss

One of the most important rules of the execution of vacuum sewerage systems equipped with 3" diameter valves is that unknown counter fall pipe sections should not be or evolve in the system (due to incorrect execution). A counter fall pipe section is such a part of the normal pipeline (so not a lift) that does not fall towards the vacuum station but rises instead. Counter fall pipe sections worsen the effeciency of a system and the vacuum levels at the ends of the vacuum mains. Incorrect pipe bedding methods and/or materials and inaccurate leveling can be the cause for their formation. The collected water at the bottom of such a counter fall pipe section causes static vacuum loss in case the water can totally fill up the cross section of the pipeline.



10. picture: A sewage plug formed in the combination of a counter fall pipe section and a lift



11. picture: A sewage plug formed in the combination of two lifts and a counter fall or horizontal pipe section in between

Total static vacuum loss along a vacuum main

The total static vacuum loss (hundred percently filled up normal state) in a system can be calculated as the sum of the vacuum losses realized along lifts, counter fall pipe sections and combinations of these. The density of the sewage is considered constant. Open lifts along a pipeline are not to be taken into account due to the fact that they do not cause any static vacuum losses.

$$\sum \Delta p_{stat} = \sum_{i=1}^{n} \rho \cdot g \cdot x'_i + \sum_{j=1}^{m'} \rho \cdot g \cdot K_j - L \cdot \rho \cdot g \cdot d + \sum_{k=1}^{z} \rho \cdot g \cdot c_k =$$

$$= \sum_{i=1}^{n} \rho \cdot g \cdot \left[\cos(45 + \alpha'_i) \cdot \sqrt{2} \cdot (e_i - d) - \sqrt{2} \cdot d \cdot \sin(\alpha'_i) \right] +$$

$$+ \sum_{j=1}^{m'} \rho \cdot g \cdot K_j - L \cdot \rho \cdot g \cdot d + \sum_{k=1}^{z} \rho \cdot g \cdot c_k =$$

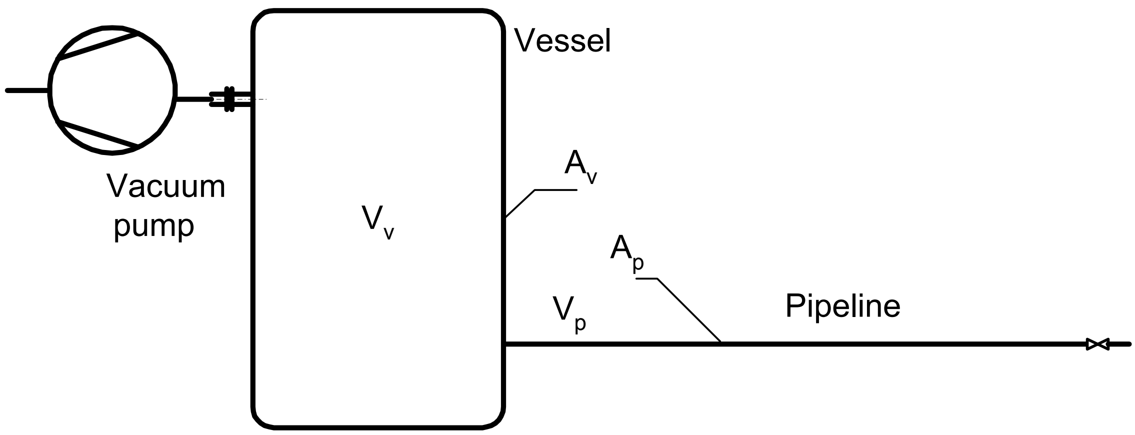
$$= \rho \cdot g \cdot \left\{ \sum_{i=1}^{n} \left[\cos(45 + \alpha'_i) \cdot \sqrt{2} \cdot (e_i - d) - \sqrt{2} \cdot d \cdot \sin(\alpha'_i) \right] + \sum_{j=1}^{m'} K_j - L \cdot d + \sum_{k=1}^{z} c_k \right\}$$

With the worked out relation the total static vacuum loss of a vacuum main can be accurately calculated both in advance and based on the as built drawings after execution of a system as well.

2.3 The Evacuation of the Pipe Network of Vacuum Sewerage Systems in the Presence of One Phase

In my researches I focused on the evacuation process of vacuum (sewerage) systems based on a model of concentrated (that assumes the unity of the thermodynamic variables /pressure, temperature and density/ at a time in the whole volume of the system) and divided parameters as well.

The thermodynamic model of the unsteady pump down process was set up both for isothermal and for general heat exchange cases. The vacuum sytem consists of a vacuum pump, a vessel and a long pipeline connected to it.

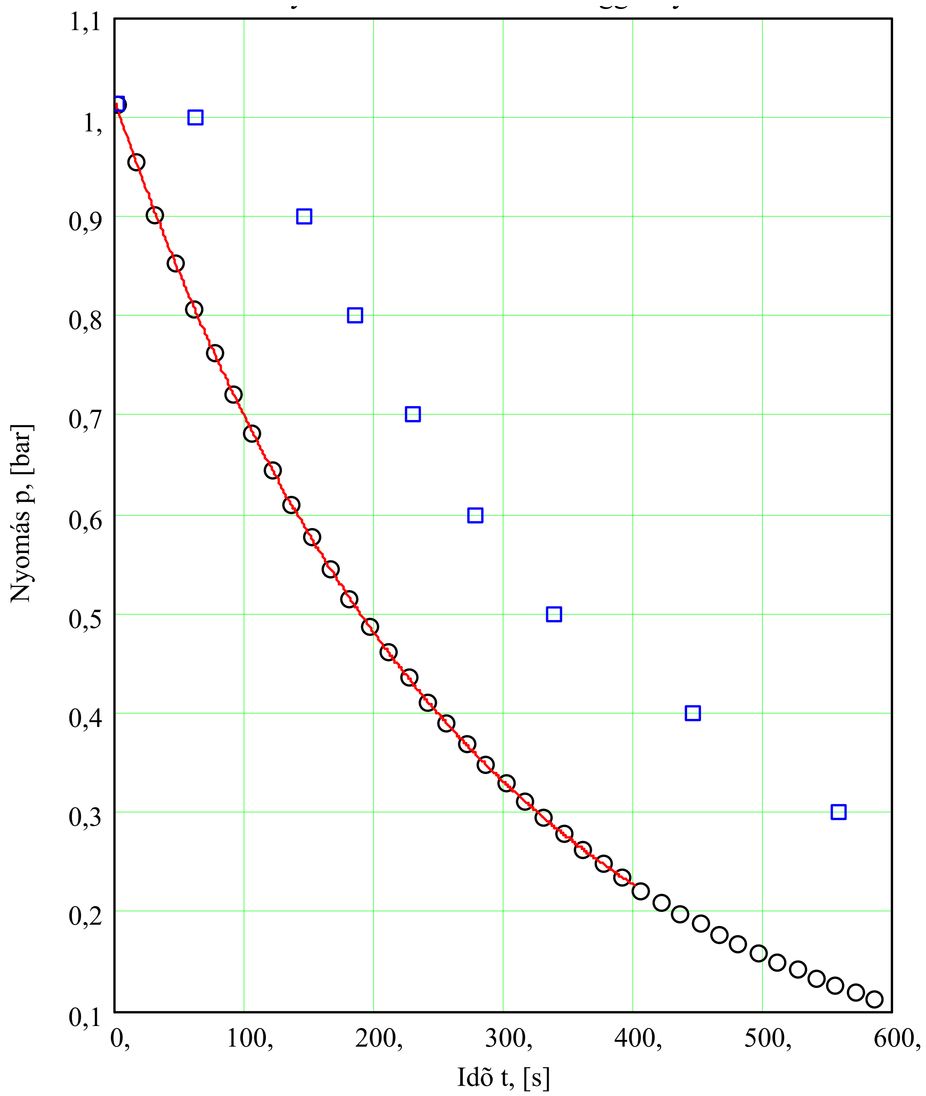


12. picture: A vacuum system that consists of a vacuum pump, a vessel and a pipeline

The calculated results based on concentrated parameters were compared with the experienced results of the measurements on the vacuum sewerage systems of Mártély, Röszke and Alattyán. The differential equations characterizing the pump down process in the general heat exchange case can only be solved numerically, so I used the software MathCad.

In Röszke the pressure gauge and data logger located at the far end of the 1790 m long pipeline collected the pressure values during the evacuation process. The figures characterizing the vacuum system and the measurement are as follows:

$p_0 = 1.013$ bar abs.	pressure at the beginning of the evacuation,
$p = 0.3$ bar abs.	pressure at the end of the evacuation at the location of measurement,
$V = 24\ m^3$	volume of the vacuum vessel,
$A_{vessel} = 50.6\ m^2$	inner surface area of the vacuum vessel,
$l = 1790$ m	length of d = 160 mm diameter SDR 17 polyethilene pipe,
$V_{pipe} = 28\ m^3$	volume of pipeline,
$A_{pipe} = 899\ m^2$	inner surface area of pipeline,
$q_v = 700\ m^3/h$	suction capacity of the Nash liquid ring vacuum pump (it is constant in the pressure range of the measurement),
$t_{measured} = 558$ s	time needed for reaching the 0.3 bar abs pressure at the location of the pressure gague.



13. picture: The pressure as a function of time in the vacuum sewerage system of Röszke during the pump down process (black circles: calculated values, general heat exchange; red line: calculated values, isothermal; blue squares: measured values)

According to my measurements 558 seconds are needed for the evacuation, whereas the isothermal chamber pump down formula gives the following result:

$$t_{isotherm} = \frac{V_0}{q_v} \cdot \ln \frac{p_0}{p} = 325.5 \text{ s.}$$

Due to the large surface of the vacuum system the simulation based on the discretional numeric method shows a nearly isothermal change of state in case the heat exchange between the vacuum system and its surroundings is characterized by $k \geq 1 W/(m^2K)$. In the general heat exchange case the calculation was done with $k=10\ W/(m^2K)$.
It became clear that the modeling of the evacuation process of vacuum sewerage systems with chamber like shapes and concentrated parameters contains exaggerated simplifications from a scientific as well as a technical point of view, therefore a model of divided parameters was applied.

The one dimensional unsteady non-adiabatic flow of a compressible agent in a pipe is characterized by the momentum

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\lambda\, v\,|v|}{2\,d} = 0 \ ,$$

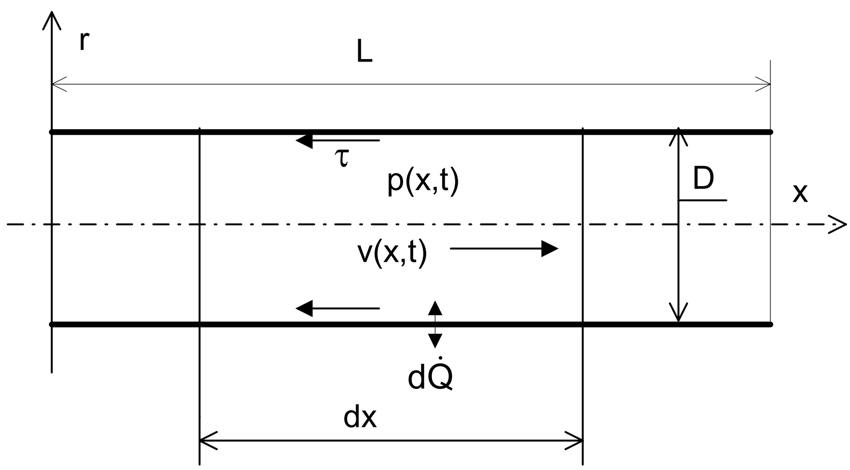
the continuity

$$\frac{\partial v}{\partial x} + \frac{1}{\rho}\left[\frac{\partial \rho}{\partial t} + v\frac{\partial \rho}{\partial x}\right] = 0,$$

and the energy equations

$$\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x} - a^2\left[\frac{\partial \rho}{\partial t} + v\frac{\partial \rho}{\partial x}\right] - (\kappa - 1)\left[\rho \cdot \frac{\lambda v^2 |v|}{2D} - \alpha \cdot \frac{4}{d}\left(\frac{p}{R \cdot \rho} - T_{cső}\right)\right] = 0 \quad .$$

For the solution of this hyperbolic quasi-linear partial differential equation (PDE) system I had to make suitable and then apply the method of characteristics and the interpolated grid method.



14. picture: Pipe section with an attached coordinate system with the one dimensional gas flow

By using the method of characteristics the three PDE-s were formed into six differential equations and these can be solved numerically. The characteristic equation pairs of the physical (x-t) plane and the space of thermodynamic variables (v, p, ρ) are the following:
(I.)

$$\frac{dv}{dt} + \frac{1}{\rho a}\frac{dp}{dt} = -\frac{\lambda \mathrm{v}|\mathrm{v}|}{2\mathrm{d}}\left[1 - (\kappa - 1)\cdot\frac{v}{a}\right] - (\kappa - 1)\cdot\frac{\alpha}{\rho \cdot a}\cdot\frac{4}{d}\left(\frac{p}{R\cdot\rho} - T_{pipe}\right)$$

$$\frac{dx}{dt} = v + a\,,$$

(II.)

$$\frac{dv}{dt}-\frac{1}{\rho a}\frac{dp}{dt}=-\frac{\lambda \mathrm{v}|\mathrm{v}|}{2\mathrm{d}}\left[1+(\kappa-1)\frac{\mathrm{v}}{\mathrm{a}}\right]+(\kappa-1)\cdot\frac{\alpha}{\rho\cdot a}\cdot\frac{4}{d}\left(\frac{p}{R\cdot\rho}-T_{pipe}\right)$$

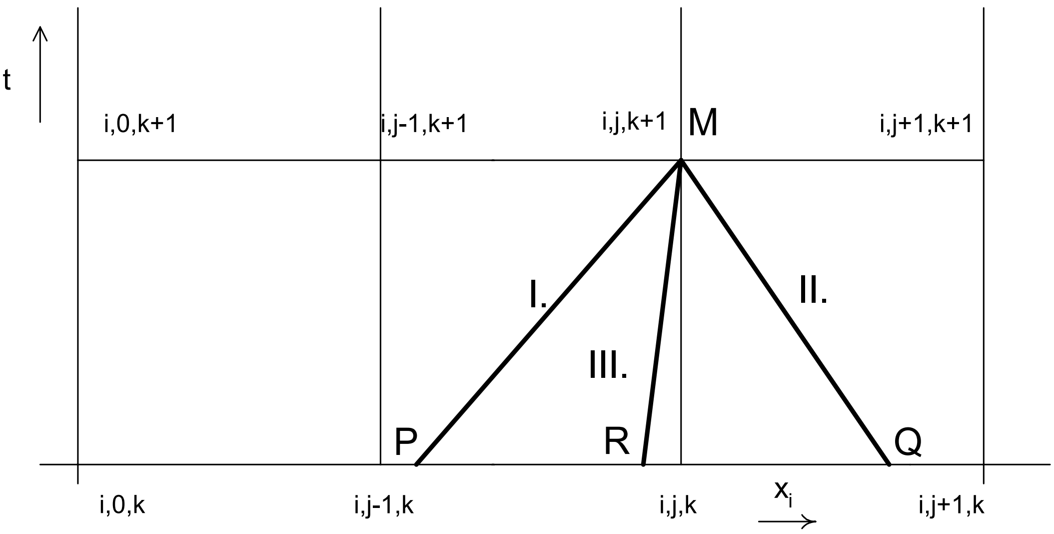
$$\frac{dx}{dt}=v-a\,,$$

(III.)

$$\frac{dp}{dt}-\kappa\frac{p}{\rho}\left(\frac{d\rho}{dt}\right)=(\kappa-1)\left[\rho\cdot\frac{\lambda v^2|v|}{2d}-\alpha\cdot\frac{4}{d}\left(\frac{p}{R\cdot\rho}-T_{pipe}\right)\right]$$

$$\frac{dx}{dt}=v\,.$$

With the help of the interpolated grid method after having integrated the equations the unknowns can be determined in the intersections of the densely laid characteristic lines starting from a known initial condition.



15. picture: Grid with the characteristic lines connected to pipe section No. i

With respect to the lengthy details I briefly outline the method. The pipeline was divided into sections having constant pipe diameter and friction coefficient and the x-t plane was given a constant Δx, Δt distance grid. Index i is used for the pipe sections, N_i stands for the number of calculation points in each section. Plane x_i-t is for section i. An i,j,k index-three belongs for each of the calculation (grid) points where i, j and k stand respectively for section, location and time.

At time k $v_{i,j,k}$, $p_{i,j,k}$ and $\rho_{i,j,k}$ values are known for example from the initial condition. I integrated the characteristic equations with linear approximation. To be able to determine the unknowns in row /k+1/, first I looked for the location of those points (P, R and Q) that are on the characteristic lines intersecting at point M, then I expressed $v_{i,j,k+1}$, $p_{i,j,k+1}$ and $\rho_{i,j,k+1}$ values from the equations. The thermodynamic variables were determined at points P, Q and R with the help of linear interpolation. Based on the following equations the thermodynamic variables at point M (i,j,k+1) can be determined:

$$v_{i,j,k+1}=\frac{B_P\rho_P a_P+B_Q\rho_Q a_Q}{\rho_Q a_Q+\rho_P a_P}\,,$$

$$p_{i,j,k+1}=(B_P-B_Q)\left(\frac{1}{\rho_P a_P}+\frac{1}{\rho_Q a_Q}\right)^{-1},$$

$$\rho_{i,j,k+1} = \frac{p_{i,j,k+1}}{a_R^{\ 2}} \text{-} B_R \, .$$

Based on these methods the unknowns can be calculated step by step starting from the initial condition (row k) except for the starting and ending points of each pipe section. At these points the connection and border conditions (closed pipe end and vessel with a vacuum pump) have to be fulfilled.

The worked out theoretical background created the conditions needed for working out a PC software with the help of which non-adiabatic unsteady gas flow in pipelines can be modeled and calculated. The results calculated by the created software verify that the use of a model of divided parameters for accurately calculating the evacuation process of volumes greatly differing from chamber like shapes – such as vacuum sewerage systems – is justified.

2.4 The Experimental Research of the Specific Energy Demand and the Hydrostatics of Vacuum Fluid Conveying on the Vacuum Sewerage Test Rig

In the experimental test rig the following can be measured: pressure in the vacuum vessel and in the pipeline at two locations; volume flow of the air and the water; energy consumption of the vacuum pump; number of cycles and air time of the vacuum valves; height of the collected water columns in the lifts.

The volumetric flow rate of water and the air time of the vacuum valves can be adjusted. The pressure in the vacuum vessel can be adjusted and maintained (by operating the vacuum pump with a frequency converter that receives signals from the pressure transmitter of the vacuum vessel).

Based on the adjusted, controlled and measured data the specific energy consumption for collecting one m^3 of water (kWh/m^3) can be calculated at different air/water ratio (m^3/m^3) and vacuum vessel pressure settings.

The pressure in the vacuum vessel was set at 0.28, 0.34, 0.4, 0.45, 0.5, 0.55 bar abs. one after another which pressure was continuously regenerated by the VFD driven vacuum pump after each opening of the vacuum valve. The biggest air/water ratio of the experiments was the maximal air cycle time that could be achieved at the actual vacuum vessel pressure. The shortest air cycle time was set at 2 seconds.

At the end of each series of test runs with the shortest air cycle time so much water was collected in the system that at the opening of the vacuum valve the intake of the water from the collection sump weakened the local vacuum to such an extent that the valve closed without letting any air in resulting in a waterlogged system and a choked operation.

Based on the series of test runs on the vacuum sewerage test rig various diagrams were prepared with the help of MathCad software to represent the

a) specific energy demand of vacuum fluid conveying as a funcion of the air/water ratio (curve parameter: vacuum vessel pressure) calculated from the measured date, and the

b) total static vacuum loss of the pipeline as a function of the air/water ratio (curve parameter: vacuum vessel pressure).

There are three main goals to be achieved at the operation of vacuum sewerage systems:

-to have the maximal reachable vacuum level at the end of each vacuum main,
-to have a reliably operating system without any inclination to choke[†] and
-to decrease the energy demand of the operation as low as possible.

Although the above mentioned parameters seem very simple and logical, they have not been simultaneously investigated in the history of vacuum sewerage systems.

The measured data show that the energy demand for transporting 1 m^3 of water is in direct proportion to the air/water ratio at each of the vacuum vessel pressure settings. Moreover it can be seen that the specific energy demand is inversely proportional to the vacuum vessel pressure level at constant air/water ratio.

The carried out measurements made it evident that the increase of the air/water ratio – up to a certain limit depending on the vacuum vessel pressure – decreases the total static vacuum loss.
The physical explanation for the reduction of the static vacuum loss is related to the fact that the water level in the lifts diminishes as the air/water ratio rises.

It also became clear from the experiments that the increase of the air/water ratio above this certain limit will not result in any additional fall in the static vacuum loss in other words there exists a minimal system syphon fullness depending on the geometry of the system that cannot be lowered any more. These specific air/water ratio points are shown on the static vacuum loss diagram and I named them **static vacuum loss moderating points**.

This fact lead to the realization that there is absolutely no point in operating a vacuum system above this certain air/water ratio because on one hand it will not make the vacuum level at the end of the pipe better, but on the other hand it will increase the energy demand of the fluid transport.

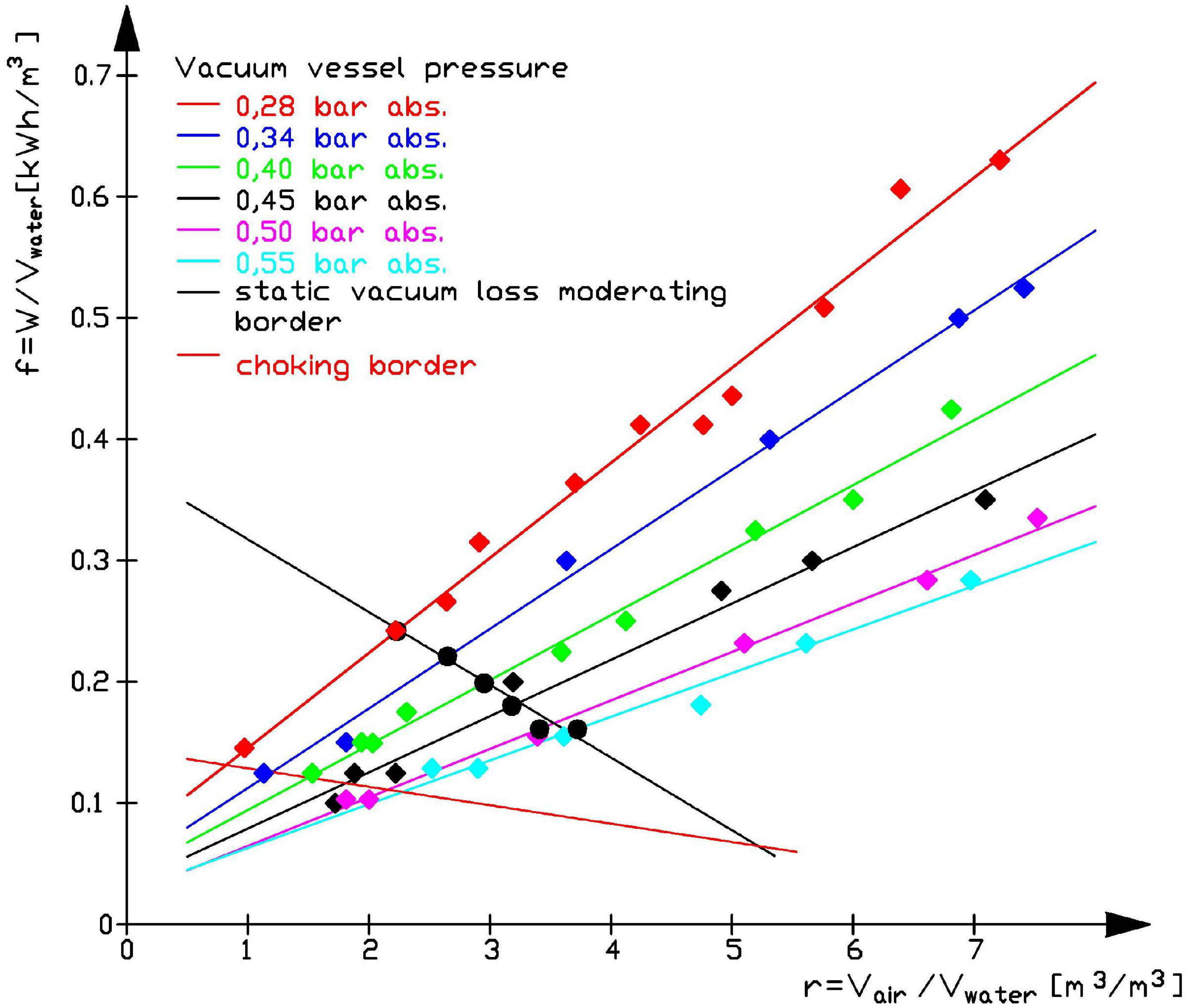
On picture No. 16. showing the specific energy demand the static vacuum loss moderating points are shown on the curves standing for different vacuum vessel pressure levels. The aligned regression line (by MathCad software) was named **static vacuum loss moderating border**.

After dealing with the upper border of the air/water ratio with regard to the rational domain of operation let us look at the lower boundary as well.
The aligned regression line on the still reliable operating points with the lowest air/water ratio was given the name **choking border**.

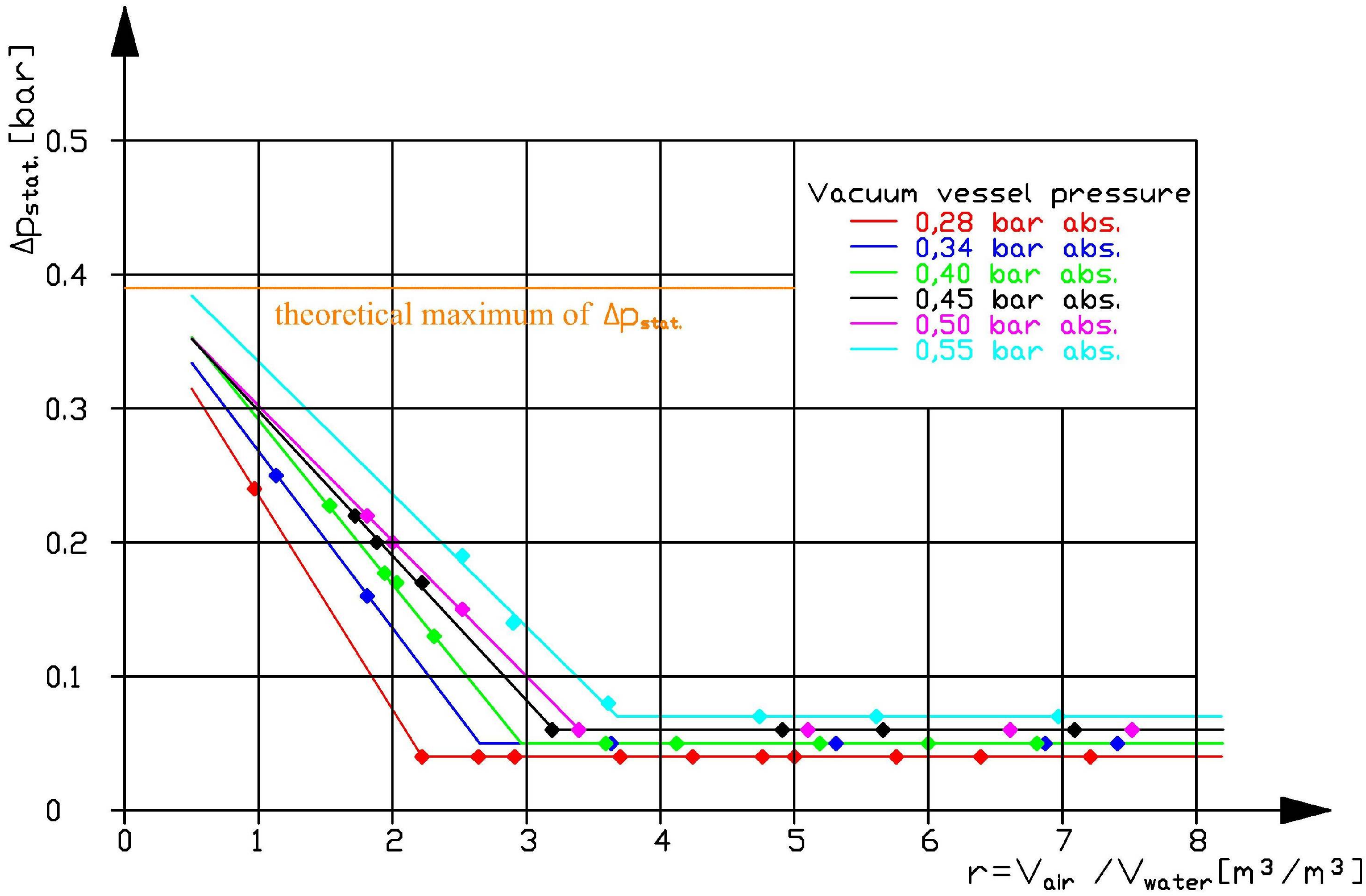
The two above mentioned border lines and the 0.28 and 0.55 bar abs. lines representing the pressure in the vacuum vessel are the borders of a quadrangular shape in the specific energy demand diagram. This area was called the **recommended domain of operation**.

Picture No. 18. is a comprehensive diagram with explanations for showing the unreliable, the energy wasting and the recommended domains of operation of vacuum fluid conveying.

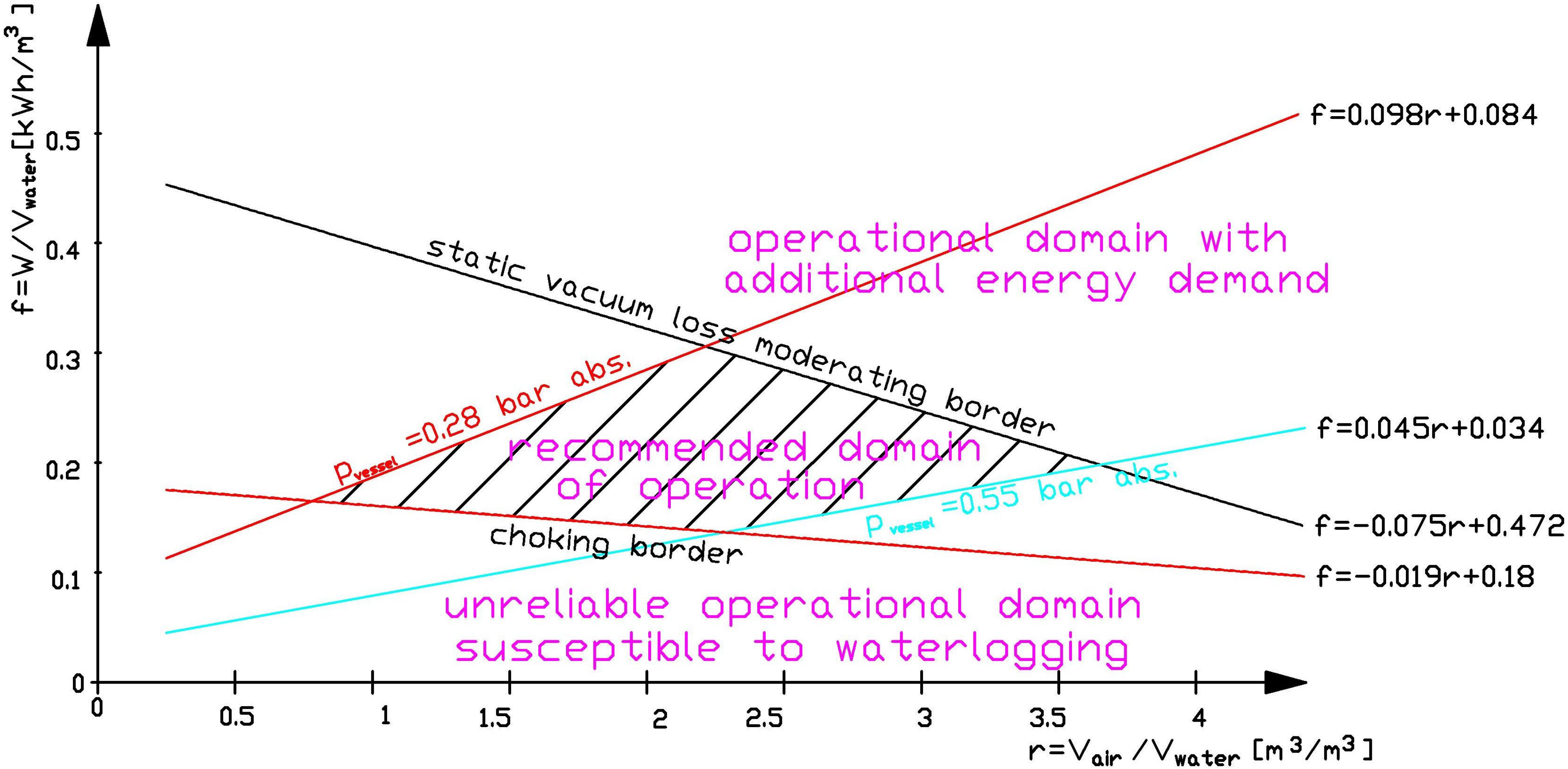
[†] The operation of the system stops if there is not enough air sucked in. In this case many long water plugs cause the static vacuum loss to be so high that at each opening of the vacuum valves less and less air is sucked in even further worsening the air/water ratio resulting in choking at the end.



16. picture: The specific energy demand of vacuum fluid conveying as a function of air/water ratio and vacuum vessel pressure



17. picture: The static vacuum loss of vacuum fluid conveying as a function of air/water ratio and vacuum vessel pressure



18. picture: The recommended operational domain of vacuum fluid conveying

The recommended working point of the vacuum fluid conveying system with 5.14 m total water elevation having 3.90 m total static vacuum loss in a hundred percently filled up normal state is located within the area of the recommended domain of operation and the optimal point of operation is in this area at the highest vacuum vessel pressure setting that still leads to reliable operation.

Conclusions drawn based on the series of measurements:
-The lower the vacuum vessel pressure, the higher the specific energy demand of vacuum fluid conveying if all other parameters remain the same.

-The specific energy demand of vacuum fluid collecting is directly proportional to the air/water ratio and the lower the vacuum vessel pressure, the steeper the line representing the relation between the air/water ratio and the specific energy demand.

-The lower the vacuum vessel pressure, the higher the volumetric ratio of the sucked in air in the system resulting in a lower water level in the lifts. Therefore the decrease in the vacuum vessel pressure monotonously decreases the total static vacuum loss of a pipeline if all other parameters remain the same.

-The decrease of the air/water ratio monotonously increases the total static vacuum loss of a pipeline if all other parameters remain the same.

-The process of vacuum fluid conveying chokes below a certain air/water ratio or above a specific vacuum vessel pressure.

-In case of a lower vacuum vessel pressure the choking of the operation of the system will take place at a lower air/water ratio.

-Operating a vacuum system above a certain air/water ratio will not result in lower static vacuum loss values along the pipelines, thus having a higher air surplus makes no sense because it is just irrational waste of energy.

-The optimal working point of vacuum fluid conveying is located between the static vacuum loss moderating and the choking borders and is at the highest vacuum vessel pressure setting still resulting reliable operation.

3. RESULTS

The determination of the hydrostatic relations depending on the profile of vacuum pipe networks:

-the static vacuum loss of a closed and an open lift was determined in the presence of two phases (water and air) in a still steady state;

-the incorrectly designed or executed pipe sections (counter fall, horizontal or incorrectly designed or built pipe sections) and the static vacuum loss caused by them were taken into stock and then I determined the total static vacuum loss (hundred percently filled up normal state) of a vacuum pipe having such faulty sections in the presence of two phases (water and air) in a still steady state.

The examination of the evacuation of a vacuum system that consists of a vacuum pump, a vacuum vessel and a pipe (network):

-the pump down process of vacuum sewerage systems was modeled with concentrated parameters;

-the evacuation process of vacuum fluid conveying systems was modeled with divided parameters;

  -the equations characterizing the non-adiabatic, unsteady flow of a compressible agent (air) in a pipeline were applied;

  -for the solution of these equations I determined the boundary conditions and applied the method of characteristics;

  -the interpolated grid method was applied and the necessary conditions (relations, initial and boundary conditions) were created for the establishment of a software capable of calculating the pump down process of a pipeline and this software was made;

-evacuation time measurements were carried out on communal vacuum sewerage systems in the presence of one phase (air).

The experimental determination of the specific energy demand of vacuum fluid conveying and the description of the explored relations:

-I designed and installed a vacuum sewerage system experimental test rig having 22 (8 normal and 7 double) lifts, 88 m DN 90 mm acrylic pipe and 5.14 m of total water lift well modeling the operation of real communal systems;

-I measured and controlled the flow rate of water and air, I measured the energy consumption of the vacuum pump, I counted the cycles of the vacuum valves, I measured the pressure in the vacuum pipe and completed a series of test runs on the experimental vacuum sewerage rig at various air/water ratio and vacuum vessel pressure settings based on which:

  -the specific energy demand of vacuum fluid conveying was determined as a function of the air/water ratio and the vacuum vessel pressure;

  -I introduced the concept of the static vacuum loss moderating and the choking borders;

  -the energetically optimal (recommended), reliable domain of operation of vacuum fluid conveying was determined.

Based on the research results regarding the hydrostatics (and energy consumption) I created a software capable of designing optimal longitudinal vacuum main profiles.

With the help of the software I designed the vacuum main profiles of the largest vacuum sewerage system in the world currently being built in the Sultanate of Oman (Seeb project, the system consists of a total of 215 km vacuum pipeline network).

The Theses of the Dissertation

1. thesis

The maximal pressure loss (static vacuum loss) in the fully filled up lift of a vacuum fluid conveying pipeline in the presence of two phases (water and air) in a still steady state state depending on the geometry of the lift can be described with the following relations

-in case of a closed lift:

$$\Delta p_{stat} = \rho \cdot g \cdot \left[\cos(45+\alpha')\cdot\sqrt{2}\cdot(e-d)-\sqrt{2}\cdot d\cdot\sin\alpha'\right]$$

-in an open lift:

$$\Delta p_{stat} = 0$$

2. thesis

The maximal pressure difference (total static vacuum loss) between the two ends of a vacuum fluid conveying pipeline having incorrect pipe sections (counter fall, horizontal or incorrectly designed or built pipe sections) in case of a hundred percently filled up normal still steady state in the presence of two phases (water and air) can be described with the following equation:

$$\sum \Delta p_{stat} =$$

$$= \rho \cdot g \cdot \left\{ \sum_{i=1}^{n} \left[\cos(45+\alpha'_i)\cdot\sqrt{2}\cdot(e_i-d)-\sqrt{2}\cdot d\cdot\sin(\alpha'_i)\right] + \sum_{j=1}^{m'} K_j - L\cdot d + \sum_{k=1}^{z} c_k \right\}$$

3. thesis

The decrease of the absolute pressure kept in the central vacuum vessel of a vacuum sewerage system – in case all other parameters remain the same – statistically assures (R^2 = 0.91 … 0.996) the increase of the specific energy demand of vacuum fluid collecting.

4. thesis

The increase of the air/water ratio – in case all other parameters remain the same –directly proportionally increases the specific energy demand of vacuum fluid conveying.

On the experimental vacuum sewerage system test rig modeling real communal conditions the aligned regression lines showing the connection between the air/water ratio and the specific energy demand of vacuum fluid collecting in case of each of the vacuum vessel pressure settings (0.28, 0.34, 0.4, 0.45, 0.5 és 0.55 bar abs.) can be described as follows (specific energy demand: $f = W/V_{water}$ = [kWh/m^3], air/water ratio: $r = V_{air}/V_{water}$ = [m^3/m^3], s and b: characterize the lines):

$$f = s \cdot r + b$$

s = 0.045 … 0.098

b = 0.031 … 0.084

r = 0.97 … 7.52

5. thesis

It is experimentally proven that the aligned regression function fit on the measured points representing the pressure difference in a still steady state between the two ends of a vacuum fluid conveying pipeline with lifts after the transport of certain amount of fluid (total static vacuum loss) – in case all other parameters remain the same – monotonously increases if the absolute pressure in the central vacuum vessel increases and/or if the air/water ratio decreases.

The process of vacuum fluid conveying chokes below a certain air/water ratio or above a specific pressure level kept in the vacuum vessel due to the undesirable waterlogging of the system.
On the experimental vacuum fluid conveying test rig modeling real communal conditions this choking border can be described with $f = -0.019 \cdot r + 0.18$ in the r = 0.82 … 2.28 range (specific energy demand: f = W/V_{water} = [kWh/m^3], air/water ratio: r = V_{air}/V_{water} = [m^3/m^3]).

6. thesis
Operating a vacuum system above a certain air/water ratio will not result in a smaller pressure difference between the two ends of a vacuum fluid conveying pipeline after the transport of certain amount of fluid in a standstill state (total static vacuum loss), thus having a higher air surplus causes a waste of energy.
On the experimental vacuum sewerage system test rig modeling real communal conditions the static vacuum loss moderating border can be described with $f = -0.075 \cdot r + 0.472$ in the r = 2.24 … 3.65 range (specific energy demand: f = W/V_{water} = [kWh/m^3], air/water ratio: r = V_{air}/V_{water} = [m^3/m^3]).

7. thesis
The energetically recommended domain of operation of vacuum fluid conveying is the area located between the static vacuum loss moderating and the choking borders and the upper and lower operational vacuum vessel pressure curves.

4. CONCLUSIONS AND SUGGESTIONS

Certain questions of this special field regarding sizing and operation are still unsolved or mostly treated based on the different experiences of the innovative predecessors often lacking solid theoretical background. I carried out researches on the hydrostatics of vacuum sewerage systems, their evacuation time and their energy demand for collecting a unit of fluid volume based on theory as well as experimenting on a vacuum sewerage pilot plant test rig designed and built by me.

I suggest that the expected total static vacuum loss of the vacuum mains be determined both at the design phase and after the execution of vacuum sewerage systems as well based on the as built drawings.

In case of commissioned vacuum sewerage systems I suggest complementing the existing requirements of the Europan Standard (MSZ EN 1091:2001) with the testing of static vacuum losses by continuously feeding water to the vacuum chamber located at the end of the vacuum main and in the meantime measuring the pressure levels and air/water ratio during the operation of the system. The measured total static vacuum loss should be compared with the calculated values. This way it is possible to find out before the real operation of a system with sewage if any hidden, problematic pipe section is to be looked after and corrected.

The research made it obvious that the equations used by vacuum valve manufacturing companies for determining the pump down time and the required vacuum pump performance of vacuum sewerage systems can be derived from the so called vessel evacuation formula based on concentrated parameters and as such they can only be used for rough calculations because they lead to inaccurate results in case of volumes greatly differing from chamber like shapes.

I suggest that for the determination of the evacuation time a correction factor depending on the overall length of a system be introduced.

I suggest that the vacuum vessel pressure level, the air/water ratio and the specific energy consumption be determined at the design phase of vacuum sewerage systems. I suggest the use of the recommended operational domain diagram when deciding the air/water ratio and the vacuum vessel pressure to be maintained.

In the European Standard of Vacuum Sewerage Systems I suggest the correction of one of the paragraphs in the hydropneumatic design of the system (MSZ EN 1091:2001, 13. p.) as follows: “the system is not to be designed so that in a standstill state the lowest planned vacuum levels should there be in the system because then there is a chance for waterlogging and choking the operation”.

5. LIST OF PROFESSIONAL PUBLICATIONS

The listing within each section has been done in chronological order.

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