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Hydraulic Conditions in Foul Water Stacks

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Abstract
Foul water stacks are a separate chapter in the design of sanitary installations, especially in high-rise buildings. The problematic part is the complicated hydraulic conditions in the stacks, which lead to high values of negative pressure and overpressure. Exceeding the maximum negative pressure values leads to the extraction of water from the traps, which causes the spread of annoying smells in the interior. Another problematic part is the high hydraulic jumps caused by a sudden change in the velocity of water in the stack, especially above the change in the direction of stacks. Such sudden changes in velocity cause excessive vibrations and noise that spread from stacks to the building structures and surrounding areas. The contribution deals with the issue of hydraulic conditions in the flow of foul water in stacks, assessment of the maximum values of negative pressure and overpressure, technical solutions that ensure optimal water flow in the drainage systems of buildings. Based on measurements that were performed in companies abroad, the authors prepared graphs of pressure fluctuations in stacks for selected boundary conditions.

Keywords
foul water stacks, hydraulic conditions in the stack, high-rise buildings, negative pressure, overpressure, the velocity of water

1 Introduction

The issue of foul water stacks in high-rise buildings is a relatively extensive and demanding topic due to complicated hydraulic conditions in the flow of foul water in drainage. Nowadays, the maximization of the use of building lands is increasing the number of building floors, which complicates the design of foul water stacks. It is necessary to base the design of stacks on foreign research and measurement because this issue is not so developed in our country. The most significant changes from mounting and design occur in buildings belonging to the I. group with 9–16 floors, Table 1 [1]. This limit is not the same for all parts of sanitary installations.

Foul water stacks must be designed so that the negative pressure and overpressure generated inside the pipe do not exceed the maximum values. When the maximum negative pressure value is exceeded, water is extracted out of the traps, and an annoying smell spreads in the building [2]. Exceeding the maximum overpressure values leads to ejecting water from the sanitary appliance. There should also be no high hydraulic jumps, which cause excessive vibration and noise due to a sudden drop in velocity of the water [3]. Hydraulic jumps most often occur above changes in stack direction. By choosing the right technical solution and stack system, it is possible to avoid several complications due to poor hydraulic conditions in the stack. Factors that affect hydraulic conditions in the stack (Fig. 1) are as follows:

- nominal diameter/dimension of the stack and branch pipe (DN/d),
- method of the stack vent – direct vent, additional vent, air admittance valve, used vent heads,
- method of connecting the branch pipes to the stack, i.e., used fittings – simple Y-branch without an inner arch, simple Y-branch with inner arch, Sovent fitting,
- the stack offset method – 88.5° elbow, 2 × 45° elbow, 2 × 45° elbow with cushioning straight pipe, simple Y-branch, Supertube system,

Table 1 Division of high-rise buildings [1]

The class	Number of floors	Height (m)
Multi-story – I. group	9–16	< 50
Multi-story – II. group	17–25	50–70
Multi-story – III. group	26–40	75–120
High	41–60	120–200
Very high	> 60	> 200

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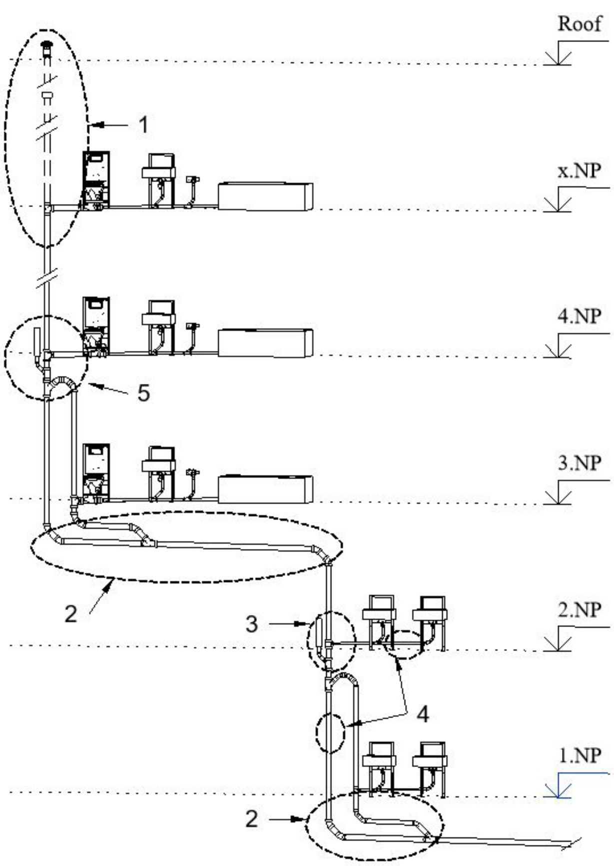

Fig. 1 Factors influencing pressure fluctuation in the stack: 1 – method of the stack vent, 2 – method of the stack transition into the drain or offset, 3 – method of connecting the branch pipe to the stack, 4 – nominal diameter/dimension of the stack and branch pipe, 5 – accessory used on the stack (Source: authors)

- method of the stack transition into the drain – examples the same as in the previous point,
- the accessory used on the stack is positive air pressure attenuators and air admittance valves on branch pipes.

2 Foul water flow in the stack

The foul water in the stack flows around the pipe's inner walls and creates a hollow cylinder with an air core in the middle [4]. At the connection points of the branch pipes with a larger flow, the air core slowly closes and creates a piston effect, which leads to negative pressure (Fig. 2).

When there is little or no foul water flow in the stack, air flows through the stack from the bottom up. This airflow creates a pressure loss, which affects the pressure fluctuations in the stack. In high-rise buildings can cause negative pressure air, which flows around the building. Other problem areas in stacks are offsets and transitions to the drainage. Changes in the direction of the stack to the drain or offset with an angle greater than 45° cause hydraulic jump due to a change in the water velocity. The water stops flowing

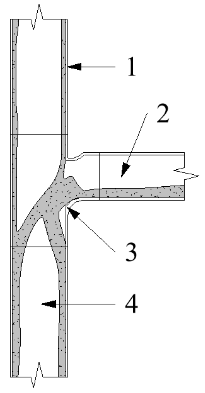

Fig. 2 Foul water flow in the stack: 1 – water flows around the inner walls of the stack, 2 – water flow from the branch pipe, 3 – formation of the piston effect, 4 – air core in the middle (Source: authors)

around the inner walls, and the pipe fills. There is overpressure above the change of direction, and negative pressure under the change of direction. Among other things, the water that hits the arch wall causes excessive vibration and noise. A significant role, in this case, has the method of the stack vent, fittings used on the stack, and the accessories.

2.1 Water flow velocity in the stack

Several measurements have been made in the past, which compared theoretical and real water velocity in stacks (Fig. 3 [5]). The orange curve represents the theoretical water velocity according to Torricelli's law. The blue curve represents the real water velocity in the stack. Curve 2 considers the air resistance and the friction on the pipe's inner walls. The graph shows that the largest increase in water velocity represents the first 10 meters of the fall. The water reaches a velocity of 10 m/s, and from this limit is the increase minimal. For this reason, it can be stated that designing offsets on the stack due to reducing the velocity is not important [6].

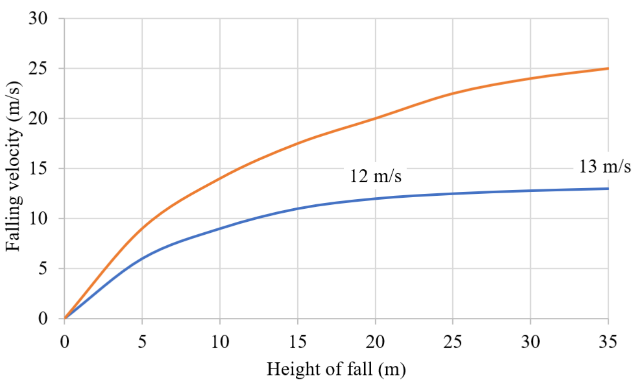

Fig. 3 Water flow velocity in the stack: the orange line shows the theoretical falling velocity, the blue line shows the real falling velocity (Adapted from [5])

2.2 Hydraulic conditions in stacks

Stack with a direct vent in high-rise buildings must be assessed. This limit is usually 70 m, but it should be even at lower heights for stacks with the larger flow. Stacked assessment is unnecessary for stacks with additional vent, stacks with Sovent fitting, and stacks with active protection elements. There are several ways to assess stacks, which are based on equations according to Dobromyslov and Wyly-Eaton formulas [7]. In the first alternative are stacks assessed for the critical length of stack L_{cr}. In the second alternative are stacks assessed for the maximum negative pressure $\Delta p_{\max}$ and maximum pressure loss when the air flows from atmosphere Δp_{op}. The article describes only one alternative for assessing stacks [8, 9].

According to the Dobromyslov formula, the maximum negative pressure in the stack $\Delta p_{\max}$ (Pa) is calculated:

$$\Delta p_{\max} = \frac{3590 \times \left[\frac{Q_{tot}}{(1+\cos\alpha)\times d_{op}^2}\right]^{1,667}}{\left(\frac{d_{op}}{d_{pp}}\right)^{0.71}} \ (\mathrm{Pa}) \quad (1)$$

where:

- Q_{tot} – total foul water flow rate in the stack (m^3/s),
- d_{op} – internal diameter of the stack (m),
- d_{pp} – internal diameter of the branch pipe (m),
- α – the angle of connection the branch pipe to stack (°).

According to the Wyly-Eaton formula, the flow of air sucked into the stack Q_a (m^3/s) is calculated:

$$Q_a = 1.5 \times Q_{tot} \times \frac{1-f}{f} \ \left(\mathrm{m^3/s}\right) \quad (2)$$

where:

- Q_{tot} – total foul water flow rate in the stack (m^3/s),
- f – degree of filling of the stack (–).

The maximum pressure loss when air flows from the atmosphere Δp_{op} (Pa) is calculated:

$$\Delta p_{op} = 2240 \times Q_a^{1.85} \times \frac{L}{d_{op}^5 \times p_a} \ (\mathrm{Pa}) \quad (3)$$

where:

- Q_a – the flow of air sucked into the stack (m^3/s),
- L – the sum of the heights of the stack and direct vent pipe (m),
- d_{op} – internal diameter of the stack (m),
- p_a – atmospheric pressure (Pa).

According to STN EN 12056-1 [10], the maximum pressure loss Δp_{op} is set at 250 Pa to maintain a minimum airflow $Q_{a,\min}$ into the stack from the atmosphere. The maximum negative pressure $\Delta p_{\max}$ should not exceed in stacks from 70–100 m value 464 Pa (Section 2.2.1). In stacks above 100 m, the sum of maximum negative pressure $\Delta p_{\max}$ and the maximum pressure loss Δp_{op} should not exceed value 464 Pa [9].

2.2.1 Maximum value of negative pressure and overpressure in the foul water stack

Traps are the only protection against the spread of annoying smells from the drainage. The water from the trap can be extracted or ejected due to high negative pressure values or overpressure values in the stack (Fig. 4).

According to STN 73 6760 [11], the minimum water height in the trap is 50 mm when it is connected to a foul water pipe and 80 mm when the trap is connected to a rainwater pipe. When designing foul water stacks in high-rise buildings is necessary to take into account the period of non-use of sanitary appliances. The non-use time of sanitary appliances dramatically influences the water level in the trap and thus on resistance against negative pressure and overpressure. Foreign research which was conducted in the 1980s confirmed that the daily average water drop in the trap is 1 mm at 20 °C. This value was not entirely accepted for two reasons. The first reason was that they did not consider the condensation of water on the inner surface of the trap, which returns and replenishes water in the trap. The second reason was that they did not consider that gases with a high content of water vapor from the branch pipe condense near the trap and also replenish the water level in the trap. For this reason, a less verified value of water drop in the trap with a value of 0.5 mm was used [1].

The highest pressure that the trap can resist, taking into account the evaporation Δp_{adm} (Pa), is calculated:

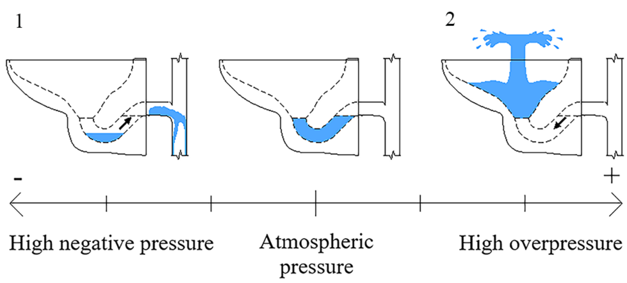

Fig. 4 Influence of pressure fluctuations on the water in the trap: 1 – extraction of water from the trap, 2 – ejection of water from the trap (Source: authors)

$$\Delta p_{adm} = 1.1 \times \rho \times g \times \left(h_{zu,tot} - h_0\right) \; (\text{Pa}) \tag{4}$$

where:

- ρ – water density (kg/m^3),
- g – gravitational acceleration (m/s^2),
- $h_{zu,tot}$ – water level in the trap (m),
- h_0 – a decrease in the water level in the trap due to evaporation (m).

Based on the obtained information about the water drop in the trap due to evaporation, we prepared a graph for the 50 mm trap (Fig. 5). After substituting the results of the water drop in the trap due to evaporation into Eq. (4), we prepared a graph for the pressure resistance of the 50 mm trap (Fig. 6). As already indicated in Section 2.2, the most commonly used height of the trap is 43 mm, which occurs after two weeks without using the sanitary appliance (day off). The resistance of the trap to pressure after this period is around 464 Pa. If it is not expected that the fixtures will not be used for more than two weeks, it is advisable to use lower values. If there are traps with a higher water height on the stack, it is possible to use higher values of pressure resistance calculated according to Eq. (4). From Figs. 5 and 6, it can be stated that the 50 mm water seal loses its ability to prevent the spread of annoying smell due to evaporation after approximately 100 days without using a sanitary appliance.

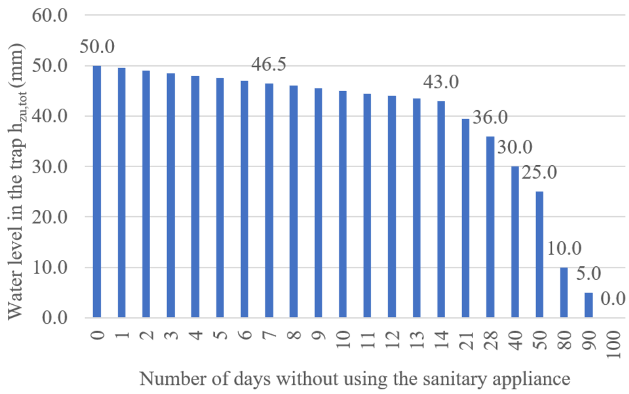

Fig. 5 Waterdrop in the trap due to evaporation (Source: authors)

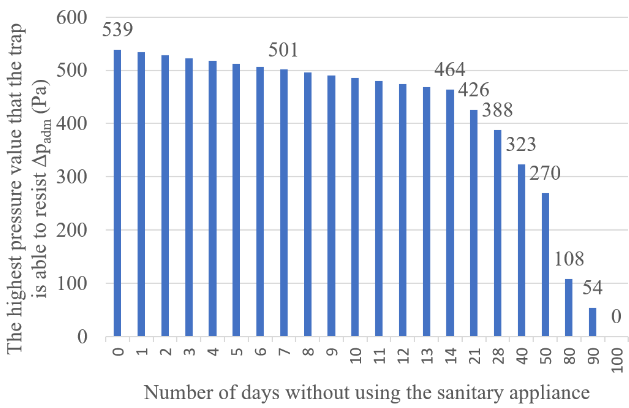

Fig. 6 Trap resistance to pressure due to evaporation (Source: authors)

3 Technical solutions of stacks

Currently, there are several stack systems which differ in technical solutions. The stack systems are as follows:

- stacks with direct vent – stack leading above the roof by direct vent pipe (Fig. 7 (b), (c), Fig. 8 I),
- stacks with additional vent – stack supplemented by additional vent (Fig. 8 II),
- stacks with Sovent fitting – branch pipes are connected to the stack by a Sovent fitting (Fig. 7 (d), Fig. 8 III, Section 3.1.1).
- stacks with active protection elements – stack equipped with active protection elements (Fig. 8 IV, Section 3.2).

Traditional stack systems, including stack with direct vent and stack with additional, are insufficient for buildings with a higher number of floors. With traditional stack systems arise material costs (larger dimensions, parallel piping of two pipes), anchoring, fire transitions, and greater space requirements for installation shafts. For this reason unique stacks systems have been developed, which include stack with Sovent fitting and stack supplemented with active protection elements. Unique systems ensure more optimal flow in stacks than traditional systems (Section 4).

3.1 Fittings used on the stack

The water from the branch pipe strikes on the stack's opposite wall and then descends downwards. The fittings used to connect the branch pipe to the stack significantly affect the hydraulic conditions in the stack (Fig. 7).

Experimental measurements have shown that when connecting the branch pipes to the stack by a simple Y-branch 45°, water can be extracted out from the trap

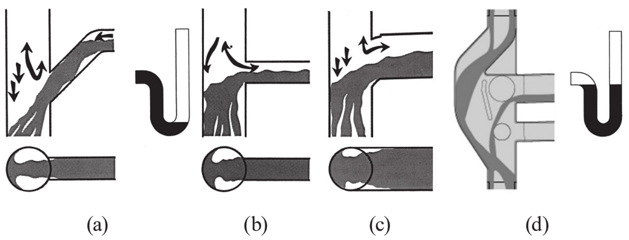

Fig. 7 Fittings on the stack: (a) simple Y-branch 45°, (b) simple Y-branch 88.5°, (c) simple Y-branch 88.5° with inner arc, (d) Sovent fitting (Adapted from [5, 12])

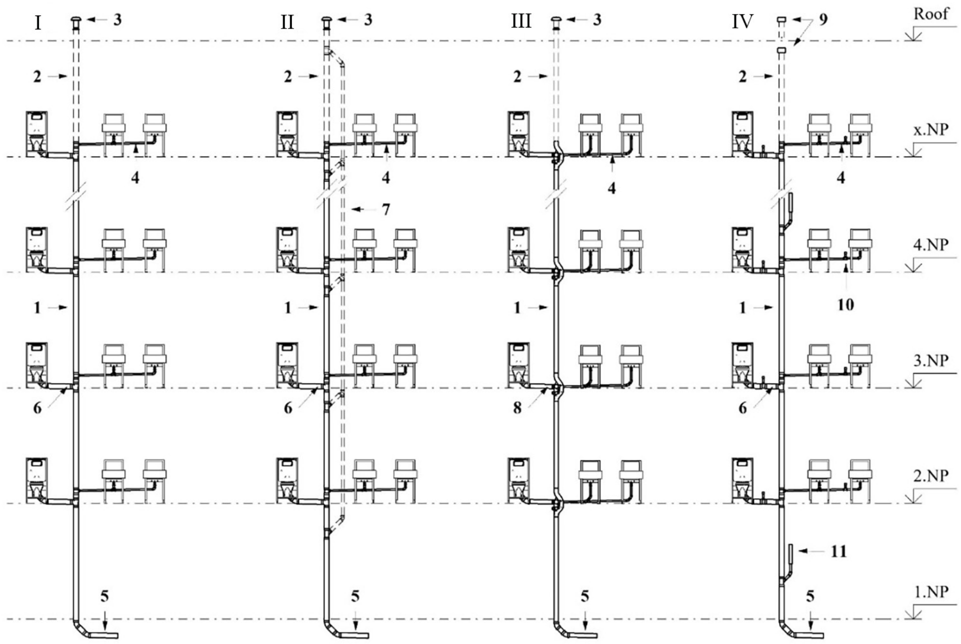

Fig. 8 Overview of technical solutions for stacks: I – stack with direct vent, II – stack with additional vent, III – stack with Sovent fitting, IV – stack with active protection elements; 1 – stack, 2 – vent pipe, 3 – vent head, 4 – branch pipe, 5 – drain, 6 – simple Y-branch, 7 – additional vent pipe, 8 – Sovent fitting, 9 – air admittance valve on the stack (above or below the roof), 10 – air admittance valve on branch pipe, 11 – positive air pressure attenuator (Source: authors)

due to negative pressure (Fig. 7 (a)) [5]. This fitting is not recommended to install on stacks. More favorable flow occurs in:

- simple Y-branch 88.5°, if the branch pipe dimension is less than DN 90 (Fig. 7 (b)),
- simple Y-branch 88.5° with inner arc, if the branch pipe dimension is DN 90 and more (Fig. 7 (c)),
- Sovent fitting (most favourable flow) (Fig. 7 (d)) [14].

When the stack's design with a simple Y-branch 88.5° is correct, the water from the trap is not extracted. These fittings also ensure optimal ventilation of branch pipes (Fig. 7 (b), (c)). With a simple Y-branch with an inner arc, it is possible to design stacks for higher maximum flows (Fig. 7 (c)).

3.1.1 Special fittings for foul water stacks

For high-rise buildings, special fittings have been designed to connect branch pipes to the stack or change the stacks' direction. These fittings include Sovent, BottomTurn, and BackFlip. BottomTurn and BackFlip fittings are used to change the direction of the stack. The BottomTurn fitting is placed at the transition of the stack to the drain or offset. The BackFlip fitting is placed at the transition of the drain or offset to the stack.

The Sovent fitting ensures the rotation of water using flow divider and swirl zone, creating a continuous column of air along with the entire stack height (Fig. 9) [12]. The main flow is directed around the connection points of branch pipes, and there is no collision between the two streams.

The BottomTurn fitting changes the flow of water using a flow divider from an annular flow to a layered flow without disrupting the continuous column of air (Fig. 10) [12]. When using this fitting, it is not necessary to connect the sanitary appliance above the offset by bypass.

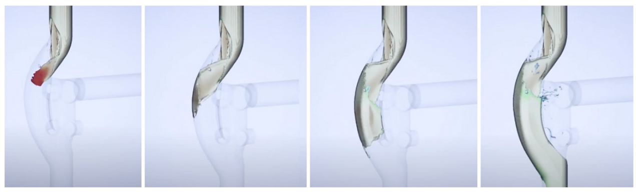

Fig. 9 Simulation of water flow in Sovent fitting (Adapted from [12])

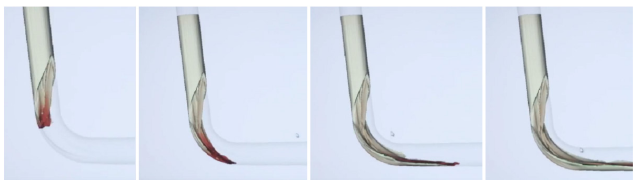

Fig. 10 Simulation of water flow in BottomTurn fitting (Adapted from [12])

The BackFlip fitting changes the flow of water using a twisted shape from a layered flow to an annular flow without disrupting the continuous column of air (Fig. 11) [12]. BottomTurn and BackFlip fittings are compatible only with Sovent fittings and cannot be used with simple Y-branches.

3.2 Active protection elements for foul water stacks

The active protection elements for foul water stacks are as follows:

- positive air pressure attenuator on the stack (Fig. 12 (a) [15]),
- air admittance valve on the stack (Fig. 12 (b)),
- air admittance valves on branch pipes (Fig. 12 (c)).

This system is almost identical to a stack system with the air admittance valve. Its advantage is that it can be used in high-rise buildings and eliminates its use in buildings with a maximum of 4 floors (L < 10 m). Due to the increasing height of the stack, active protection elements are also gradually being added:

- up to 4 floors – air admittance valve on the stack,
- from 4 to 12 floors – air admittance valve on the stack and each branch pipe,
- above 12 floors – air admittance valve on the stack and each branch pipe, positive air pressure attenuator on the stack [15].

Active protection elements prevent before creating excessive negative pressure and overpressure. Air admittance valves on branch pipes prevent excessive negative pressure, and the stack pipe can suck the required amount of air at any height. The air admittance valve on the stack prevents excessive negative pressure due to the wind, which flows around the roof of the high-rise building and opens only when negative pressure is created in the stack. The positive air pressure attenuator prevents water ejection from sanitary appliances due to overpressure, which arises above changes in the direction of the stack. The positive air pressure attenuator can also be equipped with an air admittance valve and can dampen the negative pressure. To one positive air pressure attenuator is possible to connect two stacks. In this case, for the design of the stack, stricter requirements for the location of positive air pressure attenuators are necessary.

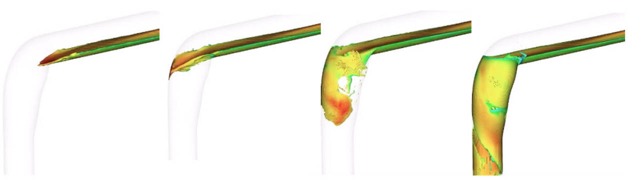

Fig. 11 Simulation of water flow in BackFlip fitting (Adapted from [12])

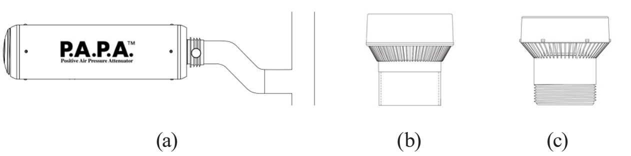

Fig. 12 Active protection elements for stacks: (a) positive air pressure attenuator, (b) air admittance valve for the stack, (c) air admittance valve for the branch pipe (Adapted from [15])

4 Experimental measurements of hydraulic conditions in stacks

The following part of the paper summarizes experimental measurements of pressure fluctuations in stacks, which were created in various foreign companies such as Geberit or Studor. In all graphs that we made from the measured results of foreign companies, the negative pressure limit with a value of 464 Pa is shown. This number represents the resistance of the trap to negative pressure after 14 days without using a sanitary appliance. When this limit is exceeded, there is no water in the 50 mm trap, which can prevent the spread of annoying smells into the interior.

4.1 Pressure fluctuations in stacks with different types of simple Y-branches

The measurement consisted of monitoring the pressure fluctuations in stacks with direct vent using simple Y-branches with different connection angles of the branch pipes. From the branch pipe DN 70 flowed water with a steady flow of 1.5 l/s to the stack DN 70.

The worst results in this measurement had simple Y-branch 70°, which exceeded the maximum value of negative pressure. At a simple Y-branch 88.5° and 45°

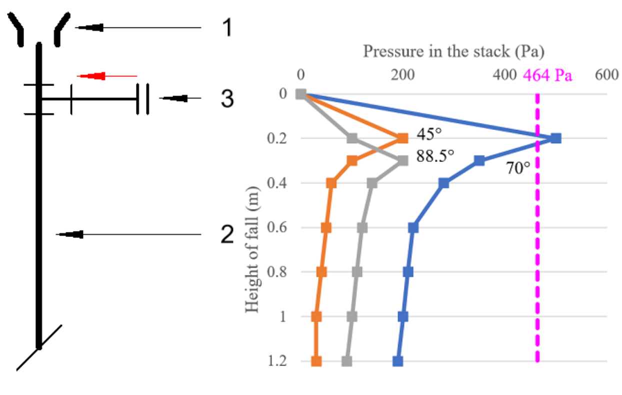

Fig. 13 Pressure fluctuations in the stack with selected simple Y-branches: the orange line shows the simple Y-branch 45°, the gray line shows the simple Y-branch 88.5°, the blue line shows the simple Y-branch 70°; 1 – air supply, 2 – stack DN 70, 3 – branch pipe with a steady flow (Adapted from [5])

did not exceed the maximum value of negative pressure (Fig. 13) [5]. This simple Y-branch 45° is not recommended to use on the stack despite of the good results (Section 3.1).

4.2 Pressure fluctuations in the stack with Sovent fitting and simple Y-branch

The measurement which was created in Geberit consisted of monitoring the pressure fluctuations in the stack with Sovent fitting and simple Y-branch 88.5° in a building with 6 floors. Two water flow states were in the stack during the measurement. The nominal diameter of the stack in a building with 6 floors was DN 100. At the first flow was flushed the toilet on the 5th floor. The pressure in the stack with a simple Y-branch 88.5° exceeded the maximum value of negative pressure on 2–5 floors. The maximum negative pressure was approximately 650 Pa. The maximum negative pressure in the stack with Sovent fitting was 200 Pa (Fig. 14) [12]. In the second flow was flushed the toilet on the 5th floor and from the 6th floor flow water with steady flow 0.5 l/s. The pressure in the stack with a simple Y-branch 88.5° exceeded the maximum value of negative pressure on all floors. The maximum negative pressure was 900 Pa. The pressure in the stack with the Sovent fitting did not significantly fluctuate compared to the first flow condition (Fig. 14). From both measurements, it can be stated that special fittings for high-rise buildings significantly eliminate the critical values of negative pressure compared to the traditional solutions.

4.3 Pressure fluctuation in the stack with direct vent and stack with active protection elements

The measurement which was created in Studor consisted of monitoring the pressure fluctuations in the stack with direct vent and stack with active protection elements in a building with 33 floors. The nominal diameter of the stack in a building with 33 floors was DN 100. Water flowed from 30–33 floors, and the maximum water flow in the stack was 6 l/s. The stack with active protection elements corresponded to the description in Section 3.2. The stack with the direct vent exceeded the maximum negative pressure on 15–29 floors. The maximum negative pressure was 1050 Pa. The stack with active protection elements did not exceed the maximum negative pressure. The maximum value of the negative pressure was 350 Pa (Fig. 15) [16]. From both measurements, it can be stated that active protection elements for high-rise buildings significantly eliminate the critical values of negative pressure compared to the traditional solutions.

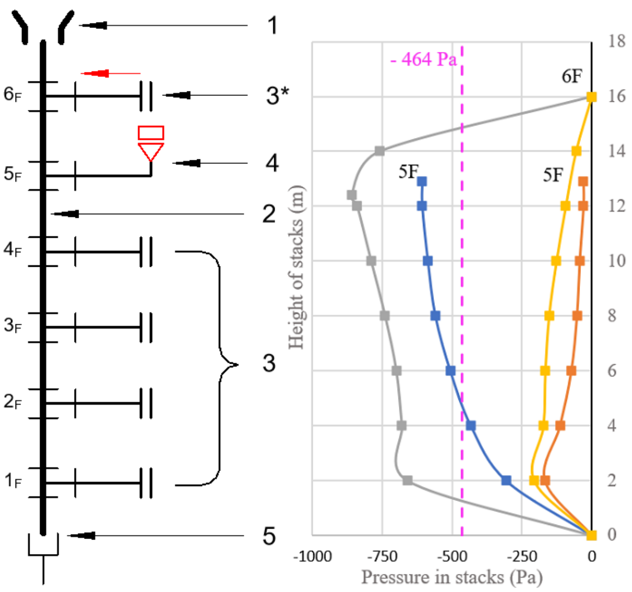

Fig. 14 Pressure fluctuations in the stack with Sovent fitting and simple Y-branch 88.5°: flushing the toilet on 5th floor: the blue line shows the simple Y-branch 88.5°, the orange line shows the Sovent fitting; flushing the toilet on 5th floor, steady flow from 6th floor: the gray line shows the simple Y-branch 88.5°, the yellow line shows the Sovent fitting; 1 – air supply, 2 – stack DN 100, 3 – branch pipe without flow, 3* – branch pipe with the flow in second flow condition, 4 – branch pipe with toilet, 5 – free discharge (Adapted from [12])

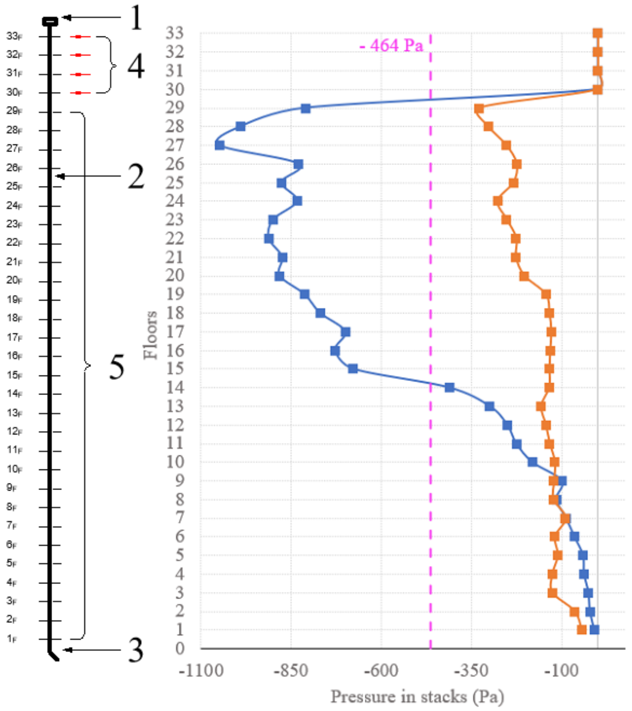

Fig. 15 Pressure fluctuations in the stack with direct vent and stack with active protection elements: the orange line shows the stack with active protection elements, the blue line shows the stack with direct vent; 1 – air admittance valve, 2 – stack DN 100, 3 – transition to the drainage, 4 – branch pipe with the flow, 5 – branch pipe without the flow (Adapted from [16])

5 Conclusion

From the analysis of hydraulic conditions in foul water stacks, it is possible to state:

- pressure fluctuation in the stack is significantly influenced by many factors (Fig. 1),
- an important detail in the design of stacks is the height of water in the trap, and it is necessary to take into account the decrease in water due to evaporation (Section 2.2.1) [17],
- with a simple Y-branch 45° on the stack may occur extraction of water from the trap due to filling cross-section of the branch pipe (Section 3.1),
- with a simple Y-branch 70° can pressure in the stack exceed the maximum value of negative pressure (Section 4.1),
- special fittings and stack systems for high-rise buildings ensure optimal water flow in the stack in comparison with traditional solutions (Sections 4.2, 4.3).

Due to the increasing number of floors in buildings, the requirements in terms of hygiene and quality of distribution systems are becoming more complicated to fulfil. For the correct design of foul water stacks in high-rise buildings, it is necessary to adhere to design and technical regulations. The design must also be based on experience and experimental measurements of foreign workplaces because this issue is not so developed in our country.

Acknowledgments

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