TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 58, Issue I, March, 2015

CLOSED EXPANSION VESSEL DIMENSIONING - PART III

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Abstract: *Closed expansion vessels require the calculation of the water volume in the heating systems. This work intends a synthetic approach by creating a new calculation for the water volume in the heating systems, comprising boilers, horizontal and vertical pipes, distribution columns, connection branches and heating elements. The proposed synthetic formula allows the determination of water volume more precisely compared to classical formulas. Thus, using the volume so determined, the authors are submitting to the attention of the professionals a new formula for dimensioning of closed expansion vessels equipped with in elastic membrane, based on the general transformation of perfect gases – Chapyeron equation. The proposed formula takes into consideration the gas pressure inside the closed expansion vessel, when filling the system and also during the operation, thus dimensioning the vessel according to their real behaviour.*

Key words*: closed expansion vessel, water volume, boiler, radiators/heating elements, air conditioning central units, heating equipment.*

1. INTRODUCTION

Dimensioning of closed expansion vessels used in the central heating systems requires the calculation of the water volume.

Obviously, a precise calculation is achievable based on the technical data sheets of the equipment and heating elements used, adding the water volume in the pipes, distribution columns which can be calculated using the materials list. The precise calculation is rather laborious, therefore the designers are usually using estimative formulas.

In usual calculations, when designing the central heating systems, the classic estimation formula is being used:

$$V_{apa} = 30 \cdot Q_{INST} + 10 \cdot (Q_{ACM} + Q_{VENT}); \quad [l] \qquad (1)$$

where: Q_{INST} – total power of the heating plant, in [kW];

Q_{ACM} – total power of the boilers for domestic hot water, in [kW];

Q_{VENT} – total power of the air handling units (CTA) in the ventilation systems, in [kW].

2. CALCULATION FORMULA OF WATER IN THE CENTRAL HEATING SYSTEM

Based on the algorithm shown in the previous works [1, 2], the general relation has been determined, thus allowing the calculation of the overall water volume in the heating system which comprises:

- water volume of boilers, equipment and pipes inside the heating plant [1] determined based on the following initial data:

$\sum V_{CZi}$ – sum of water volumes inside of boilers – optional, in [l], based on the technical data sheets, if the boilers are known;

Q_{INST}^{CT} - total power of the heating plant, in [kW];

n_{RAC}^{BEP} - total number of the tank equaliser connections;

$n_{RAC}^{D/C}$ - total number of the supply/return manifold connections;

Q_{ACM} - total power of the boilers or plate heat exchanger for domestic hot water, in [kW].

Consequently, taking into consideration the nature of the fuel used, the general formula is:

$$V_{APA}^{CT} = \begin{cases} gas, liquid\ \ fuel \begin{cases} 1.04 \cdot \sum V_{CZi} \\ 2.08 \cdot Q_{INST}^{CT} \end{cases} \\ pellets \begin{cases} 1.04 \cdot \sum V_{CZi} \\ 5.86 \cdot Q_{INST}^{CT} \end{cases} \\ wood\ \ remnants, briquettes \begin{cases} 1.04 \cdot \sum V_{CZi} + 15.0 \cdot Q_{INST}^{CT} + \\ 19.11 \cdot Q_{INST}^{CT} \end{cases} \\ gasification \begin{cases} 1.04 \cdot \sum V_{CZi} + 55.0 \cdot Q_{INST}^{CT} \\ 59.68 \cdot Q_{INST}^{CT} \end{cases} \end{cases}$$

$$+ \left(0.082 \cdot n_{RAC}^{BEP} + 0.027 \cdot n_{RAC}^{D/C} + 0.88\right) \cdot Q_{INST}^{CT} + C_{ACM} \cdot Q_{ACM} \quad [l] \qquad (2)$$

where: C_{ACM} - is the coefficient for the calculation of the water volume inside the devices to prepare domestic hot water, having the following values:

- for boilers (B): $C_{ACM}^{B} = 0.23$ l/kW$_{ACM}$;
- for plate heat exchangers (SPP): $C_{ACM}^{SPP} = 0.069$, in l/kW$_{ACM}$.

● <u>heating elements water volume</u> [2] requires the following initial data:

Q_{INST}^{CI} - total heat load of different types of heating elements, in [kW];

and also the connection mode to the columns of the heating elements – direct connection or through a manifold, characterized by the connection correction coefficient: $C_{RAC\ CI}^{CI}$, having the values shown in tab. 1.

Therefore, the general formula has been achieved:

$$V_{APA}^{CI} = \sum C_{RAC\ CI}^{CI} \cdot V_{APA}^{u} \cdot Q_{INST}^{CI}; \quad [l] \qquad (3)$$

where: V_{APA}^{u} - unit volume of heating elements, in [l/kW], shown in tab. 1;

● <u>water volume of the air handling units</u> [2], requires the following initial data:

Q_{INST}^{CTA} - installed heat load of heating coils in the air handling unit (CTA), in [kW], resulting the formula:

$$V_{APA}^{CTA} = 0.17 \cdot Q_{INST}^{CTA}; \quad [l] \qquad (3')$$

● <u>water volume of the distribution pipes and columns</u> [2], requires the following initial data:

Q_{INST}^{CI} - overall installed heat load of the various heating elements, in [kW];

n_{niv} – building number of floors;

h_{niv} – floor height including the slab, in [m];

P – building perimeter, in [m],

thus resulting the general formula:

$$V_{APA}^{COL+DISTRCI} = \sum \left[V_{APA}^{CDu} \left(C_{COL}^{CI} (n_{niv} - 1) h_{niv} + \frac{P}{2} \right) \right] \cdot Q_{INST}^{CI} \quad [l] \qquad (4)$$

Table 1

Unit water volume of heating elements and connection correction coefficient

Heating element	Type of element	Unit volume of heating elements V_{APA}^{u} [l/kW]	Column connection mode	Connection correction coefficient $C_{RAC\ CI}^{CI}$
RADIATORS	Steel panel radiator	3.84	directly to column	1.15
			using manifolds	1.89
	Cast iron radiator	13.66	directly to column	1.06
			using manifolds	1.38
FAN COILS (VCV)	Floor fan coil	0.55	directly to column	1.60
			using manifolds	4.22
	Ceiling fan coil	0.82	using manifolds	6.84
UNDER FLOOR HEATING		5.25	using manifolds	1.00
WALLS HEATING		1.85	using manifolds	1.00

where: $V_{APA}^{CD\ u}$ - unitary volume of water in columns and distribution, in [l/kW], having the following values:

- radiators columns and distribution:

$$V_{APA}^{CD\ RAD} = 0.025\ l/kW;\backslash$$

- fan coils columns and distribution:

$$V_{APA}^{CD\ RAD} = 0.049\ l/kW;$$

- under floors/walls heating columns and distribution: $V_{APA}^{CD\ RAD} = 0.025\ l/kW;$

C_{COL}^{CI} - correction coefficient of the weighted average, shown in the work [2].

It should be mentioned that beside the extension of the database comprising plant and equipment of the heating plant and heating elements, it is necessary to analyse possibility to estimate the water volume in the heating networks.

3. COMPARISON BETWEEN THE PROPOSED AND CLASSICAL FORMULAS

In order to demonstrate the major differences between the values of heating water volume, the calculation using both formulas has been performed for several buildings with different destinations – where the technical design was carried out by the authors. The results of the calculation and the exact water volume based on the materials list are shown in tab. 2.

Therefore, analysing the values based on the calculation using the proposed formula, compared to the classic formula, it results a massive over-dimensioning of water volume as follows:

- for systems using steel panel radiators the over-dimensioning is within the range of 225 - 250 %;
- for systems using floor fan-coils and steel panels (in the classical formula the fan-coils VCV have been considered as ventilation systems) the over-dimensioning is about 180 %.
- for the classical systems using cast iron radiators, the over-dimensioning is about 150 %.

Table 2

Water volume according to the proposed formula, classical formula and real volume

Initial Data	Symbol	U.M.	Building destination		
			Housing	Offices	Hotel
Heating plant power	Q_{INST}^{CT}	kW	880	340	460
B.E.P.connections number	n_{RACBEP}	buc	4	4	4
D/C connections manifold number	$n_{RACD/C}$	buc	7	3	6
Boiler's total heat load	Q_{ACM}^{B}	kW			
Heat exchanger load SPP	Q_{ACM}^{SPP}	kW	260		240
Heat load panel radiators	Q_{INST}^{RAD}	kW	696	56.8	154
Heat load VCV floor	Q_{INST}^{VCV}	kW	0	271.2	284.4
Heating elements connection			manifold		
Number of levels	n_{niv}		7	3	8
Average floor height	h_{niv}	m	2.7	4	3.2
Exterior building perimeter	P	m	218	248	176
Water volume under proposed formula		l	10,331	4,149	5,366
Water volume under classic formula		l	23,480	10,200	9,864
Classic/proposed formula ratio		%	227.3	245.8	183.8
Real water volume		l	8,315	3,650	4328
Classic/real ratio		%	282.4	279.5	227.9
Proposed/real ratio		%	124.3	113.7	123.9

4. CALCULATION OF WATER VOLUME IN CLOSED EXPANSION VESSEL

For the central heating systems using water, it is possible to have over pressure, due to water expansion. Safety measures against over-pressure are aiming at taking over the water expansion – through expansion vessels, discharging water excess through overflow or safety valves and also insuring an operation pressure in the system, which should not exceed the allowable pressure. Moreover, the open expansion vessels allow: insuring the water level which should be higher than the highest installed heating element, providing a small water reserve and removing the air in the installation. Using open expansion vessel has the following disadvantages: they are favouring the corrosion having direct air contact, the installing height which often requires special structures calculated to withstand the load and earthquakes, risk of flooding in case of damages and a relatively high number of connection pipes and fittings. In the case of modern heating systems the above mentioned disadvantages have led to abandoning the open expansion vessels, swithching to closed expansion vessels as a measure to protect the installation for over pressur and also using safety valves as indicated by the technical norms in force [3]. It is to be mentioned that for small boilers (tenths of kW) using solid fuel, the technical prescriptions in some European countries (Czech Rep. , Italy) it is compulsory to use open expansion vessels. The technical norms in Germany, Switzerland are only recommending the use of closed expansion vessels, if the boiler is provided with automatic thermal discharge. It consists of a coil installed in the pressurised boiler body, connected to the cold water supply and a thermo-valve controlled by a heat thermal sensor, in case of overheating.

4.1. Calculation of water volume increase

Regardless of the expansion vessel type, it must allow the compensation of water expansion ΔV, in [l], due to the difference between the filling temperature and average temperature under normal operation conditions, as per the following formula:

$$\Delta V = V_{INST} \cdot \left(\frac{\upsilon_m}{\upsilon_{10}} - 1 \right) ; \quad [l] \qquad (5)$$

where: V_{INST} – water volume of the central heating system , in [l];

ϑ_m – specific water volume at the average operating temperature – arithmetical average between the supply and return temperatures, in [l/kg], taken from the tables comprising the water thermodynamic properties;

ϑ_{10} – specific water volume at the filling temperature – considered as per regulations 10 ^{0}C, ϑ_{10} = 1.0004 l/kg.

A particular problem is the selection of number of closed expansion vessels, which is not provided in the norms [3, 4, 5] and standards. The authors are considering that the specifications in the standard STAS 7132-86 – dealing with the closed expansion vessels *without elastic membrane* (water being therefore in direct contact with the pressureized air) are obsolete in relation with the current heating systems.

The authors are considering that when adopting the number of closed expansion vessels it is to be taken into consideration:

- for small heating plants ($Q_{INST}^{CT} \leq 100$ kW) are usually provided with one boiler, therefore one expansion vessel. Thus for the calculation of water increase (see formula 5), it is considered the total volume of hot water from the boilers (see formula 2), heating elements (see formula 3) and distribution pipes (see formula 4).

- heating plants ranging between hundreds and thousands kW ($Q_{INST}^{CT} > 100$ kW) – according to the regulations, are provided with several boilers (not necessarily with a reserve boiler), as follows:

- heating plants: $Q_{INST}^{CT} = 100 \div 2.000$ kW – two boilers;
- heating plants: $Q_{INST}^{CT} > 2.000$ kW – three boilers.

German regulations DIN 4751 T2 provide the obligation for each boiler to be protected against overpressure, both by safety valves and closed expansion vessels, directly connected. Generally, the closed expansion vessel is installed on the return pipe, without any isolating fitting, eventually an isolating valve, sealed in open position which should allow the intervention without emptying the system.

The compensation of the remaining volume in the heating system, comprising the equipment in the heating plant (except boilers), heating elements and distribution pipes is provided through closed expansion vessels installed either on the return pipes or on the pressure equalizing vessel.

Therefore the calculation of the water volume is made as follows:

- calculation of the closed expansion vessel volume belonging to each boiler is made by taking into consideration the volume of the boiler, recirculating pipe and eventually the common rail (part of the value resulting from formula 2);
- calculation of the closed expansion vessel/s volume belonging to the heating system is based on the water volume of the pipes and equipment in the heating plant (part of formula 2, except fior boilers), heating elements (formula 3) and distribution pipes (formula 4).

4.2. Calculation of the closed expansion vessel volume

Technical norms in force [4, 5] recommend the use of closed expansion vessels with an elastic membrane between the hot water and the pressure gas. Main advantage compared to the ones without elastic membrane is that it prevents air dissolving into the water, thus reducing the corrosion and eliminating the loss of the heating agent.

The formula indicated in the specialized literature, taken from the standard STAS 7132-86, allows the calculation of closed expansion vessel based on the formula:

$$V = 1{,}1 \cdot \Delta V \cdot \frac{1}{1 - \frac{p_{min}}{p_{max}}}; \qquad [l] \qquad (6)$$

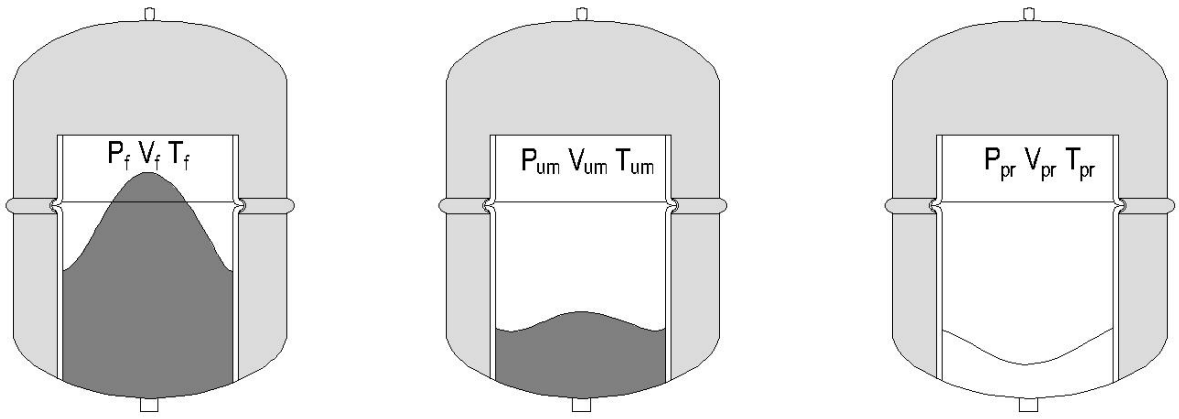
where: p_{min} – is the minimum absolute pressure in the central heating system, in [bar], determined by the hydrostatic pressure of the water column comprised between the most upper heating element and the expansion vessel – H, in [m], increased by 1,5 ÷ 2 m (0.15÷0.2 bar), as per the formula:

$$p_{min} = \frac{H}{10} + (0.15 \div 0.2) + 1 \; ; \quad [bar]$$

P_{max} – maximum absolute pressure of opening the safety valves, in [bar], based on the allowable pressures of heating installation elements.

It is to be mentioned that the calculation formula is specific for closed expansion vessels without elastic membrane, as it does not take into account the precharged pressure.

From the constructive point of view, the expansion vessels currently used in the heating systems are provided with an elastic membrane, precharged with nitrogen or pressurized air.



a – closed expansion vessel in precharged status

b – closed expansion vessel in filling status

c – closed expansion vessel in operation status

Fig. 1. Closed expansion vessel – gas layer status

Related to the closed expansion vessel with elastic membrane, shown as principle in fig. 1, the following situation have to be considered:

● gas layer parameters in precharged status – fig. 1.a:
- precharged pressure as per the technical data sheet of closed expansion vessel: p_{pr} – absolute pressure, in [bar];
- volume of gas layer representing the overall volume of expansion vessel: V_{pr} in [l];
- temperature of gas layer – practically the temperature of the environment: T_{pr} – absolute temperature, in [K];

● gas layer parameters in filling status – fig. 1.b:
- filling pressure representing the minimum absolute pressure: $p_{um} = p_{min}$ – absolute pressure in [bar];
- volume of gas layer corresponding to filling pressure: V_{um} in [l];
- temperature of gas layer – practically the temperature during the filling of the system: T_{um} - absolute temperature, in [K], it is considered $10\ ^0C = 283.15$ K;

● gas layer parameters in operation – fig. 1.c:
- maximum absolute pressure in the system, representing the absolute pressure of opening the safety valves: $p_f = p_{max}$ - absolute pressure, in [bar];
- volume of gas layer corresponding to maximum pressure: V_f in [l];
- gas layer temperature: T_f - absolute temperature, in [K].

4.2.1. Calculation of closed expansion vessel based on isotherm transformation

As a first approximation it can be considered that the gas layer temperature remains practically constant - the environmental temperature – as the water in the system does not pass through the vessel. Practically the expansion vessel takes over only the surplus due to water expansion of hot water.

The gas layer goes through an isotherm transformation from the precharged to filling to operation statuses, according to Boyle-Mariotte rule (p·v = const.), thus resulting the formula:

$$p_{pr} \cdot V_{pr} = p_{um} \cdot V_{um} = p_f \cdot V_f \ ;$$

which allows based on the initial status – precharged, the determination of the gas layer pressure during filling:

$$V_{um} = \frac{p_{pr} \cdot V_{pr}}{p_{um}} \ ; \quad [l]$$

respectively, gas layer volume during operation:

$$V_f = \frac{p_{pr} \cdot V_{pr}}{p_f} \ .$$

Obviously, the difference of gas volume between filling and operation allows the water expansion, as per the following formula:

$$\Delta V = V_{um} - V_f = \frac{p_{pr} \cdot V_{pr}}{p_{um}} - \frac{p_{pr} \cdot V_{pr}}{p_f} = p_{pr} \cdot V_{pr} \cdot \frac{p_f - p_{um}}{p_{um} \cdot p_f} \quad [l] \qquad (7)$$

Based on formula (7), the expansion vessel is determined:

$$V_{pr} = \Delta V \frac{p_{um} \cdot p_f}{p_{pr} \cdot (p_f - p_{um})} . \quad [l]$$

Consequently it results that the volume of expansion vessel is:

$$V_{VEI} = 1{,}1 \cdot \Delta V \cdot \frac{p_{min} \cdot p_{max}}{p_{pr} \cdot (p_{max} - p_{min})} . \ [l] \qquad (8)$$

In the formula the volume of expansion vessel, the usable volume has been increased by 10 % compared to recommendation of technical regulations.

4.2.2. Calculation of expansion vessel capacity based on general transformation

The precise calculation requires taking into consideration the variation of all parameters corresponding to the three statuses: precharged-filling-operation according to the perfect gas equation – Clapeyron formula ($\frac{p \cdot V}{T} = \text{const.}$), thus resulting the formula:

$$\frac{p_{pr} \cdot V_{pr}}{T_{pr}} = \frac{p_{um} \cdot V_{um}}{T_{um}} = \frac{p_f \cdot V_f}{T_f} \; ;$$

which allows based on the precharged status the determination of gas layer volume, during filling:

$$V_{um} = \frac{p_{pr}}{p_{um}} \cdot \frac{T_{um}}{T_{pr}} \cdot V_{pr} ; \qquad [l]$$

respectively, gas layer volume during operation:

$$V_f = \frac{p_{pr}}{p_f} \cdot \frac{T_f}{T_{pr}} \cdot V_{pr} \; . \qquad [l]$$

Obviously, the difference between the gas volume between filling and operation allows the water expansion as per following formula:

$$\Delta V = V_{um} - V_f = \frac{p_{pr}}{p_{um}} \cdot \frac{T_{um}}{T_{pr}} \cdot V_{pr} - \frac{p_{pr}}{p_f} \cdot \frac{T_f}{T_{pr}} \cdot V_{pr} =$$

$$= V_{pr} \cdot \left(\frac{p_{pr}}{p_{um}} \cdot \frac{T_{um}}{T_{pr}} - \frac{p_{pr}}{p_f} \cdot \frac{T_f}{T_{pr}} \right) \qquad [l]$$

By simplifying, it can be considered that the precharged and filling temperatures are equal: $T_{pr} = T_{um}$, resulting:

$$\Delta V = V_{pr} \cdot \left(\frac{p_{pr}}{p_{um}} - \frac{p_{pr}}{p_f} \cdot \frac{T_f}{T_{pr}} \right) =$$

$$= V_{pr} \cdot \frac{p_{pr}}{p_{um} \cdot p_f} \cdot \left(p_f - p_{um} \cdot \frac{T_f}{T_{pr}} \right) . \qquad [l] \qquad (9)$$

Based on the formula (9), the expansion vessel volume is:

$$V_{pr} = \Delta V \cdot \frac{p_{um} \cdot p_f}{p_{pr} \cdot \left(p_f - p_{um} \cdot \frac{T_f}{T_{pr}} \right)} . \qquad [l]$$

The expansion vessel volume can be calculated using the following formula:

$$V_{VEI} = 1{,}1 \cdot \Delta V \cdot \frac{p_{min} \cdot p_{max}}{p_{pr} \cdot \left(p_{max} - p_{min} \cdot \frac{T_f}{T_{pr}} \right)} . \; [l] \; (10)$$

The gas layer temperature in the expansion vessel during operation is considered to be equal to the average between absolute filling temperature and absolute temperature of the return water, as the vessel is installed on the return pipe and the water does not circulate through the expansion vessel:

$$T_f = \frac{T_{pr} + (t_{retur} + 273{,}15)}{2} \; . \qquad [K]$$

5. CONCLUSIONS

The formula proposed by the authors for dimensioning the closed expansion vessels allows dimensioning of expansion vessels more accurately compared to the formulas in the current technical literature.

If the proposed logical and calculation algorithm is interesting to professionals, it is necessary to expand the database about the equipment used in the heating plants, heating elements and to obtain a formula to estimate the water volume in thermal networks. This expansion of database will allow an analysis – as much as possible, of all alternatives existing in the area of central heating systems.

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CALCULUL VASELOR DE EXPANSIUNE ÎNCHISE – PARTEA III-A

Rezumat Dimensionarea vaselor de expansiune închise necesită calculul volumului apei calde din instalaţiile de încălzire centrală. Lucrarea sistematizează algoritmul de calcul al acestuia, prin deducerea unei noi relaţii de calcul al volumului apei din utilajele şi echipamentele centralei termice, din conductele orizontale şi coloanele de distribuţie, precum şi din corpurile de încălzire. Relaţia sintetică propusă permite determinarea cu un grad de precizie superior relaţiilor clasice a volumului apei din instalaţiile de încălzire centrală. Utilizând volumul apei astfel determinat, autorii propun atenţiei specialiştilor o nouă relaţie de dimensionare a vaselor de expansiune închise cu membrană elastică pe baza transformării generale a gazului perfect – ecuaţia lui Clapeyron. Relaţia propusă ia în considerare parametrii pernei de gaz la starea de preîncărcare, la umplerea instalaţiei cât şi din timpul funcţionării, ceea ce permite dimensionarea vaselor de expansiune închise conform comportării reale a acestora.

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