7.
Technical appendix

PROPORTIONAL ZONE CONTROLS

7.1 Two-way control valves

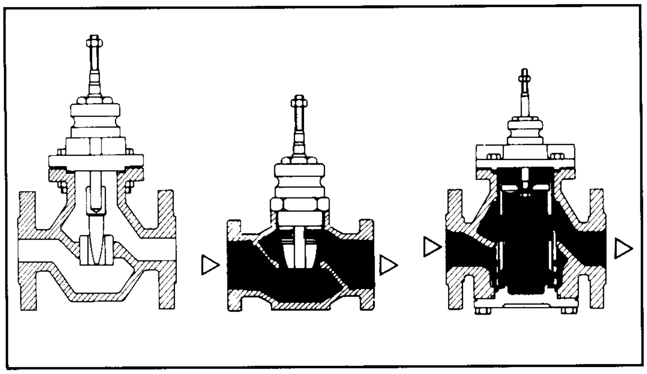


Fig. 43. Two-way control valve types

7.1.1 Without secondary pump

A proportional two-way valve V1 controls the water flow through coil C1 (Figure 44) to regulate the output. The pressure drop across the control valve should be selected with 50% of the pressure drop available between the supply and return riser. Therefore, the pressure drop through coil C1, balancing valve CBV 1, and connecting pipe should not be larger or equal to 50% of ΔH.

$$\Delta H = \Delta Pv + \Delta Pc + \Delta Pb + \Delta P(\text{piping})$$

$$\Delta Pv \geq 0.50\Delta H$$

$$Cv = \frac{\text{USGPM}}{0.66\sqrt{\Delta Pv(\text{ft})}}$$

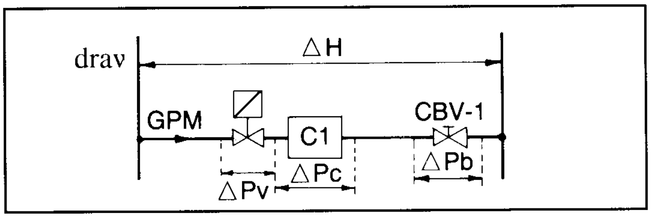
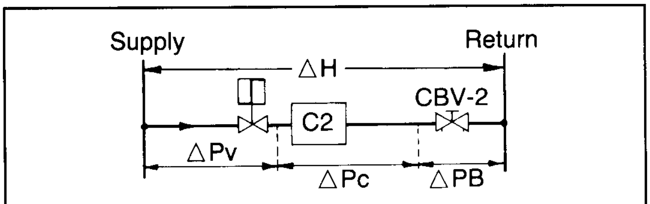


Fig. 44. Terminal with proportional valve and balancing valve

The valve CBV-1 is used:

- during the balancing of the installation
- as a service valve
- to check the flow if a problem occurs



$$\Delta PB = \Delta H - \Delta Pv - \Delta Pc$$

Fig. 45. Terminal with ON/OFF valve and balancing valve

When the control valve is working in "ON/OFF" the balancing valve CBV-2 is adjusted to obtain the right flow with the control valve fully open.

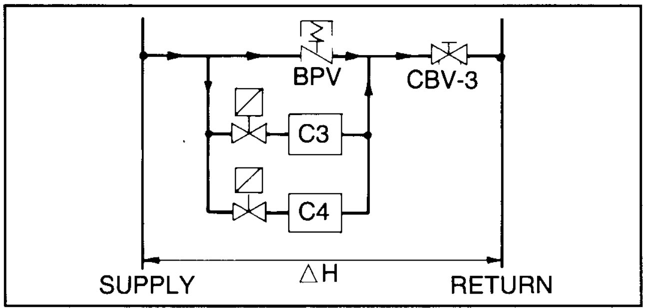


Fig. 46. Terminals with proportional valves with small Cv, and high ΔH

When proportional control valves are used, it may be difficult to find Cv values small enough to take at least 50% of the total differential pressure ΔH.

In this case, the differential pressure can be kept constant at an acceptable value with a BPV (By Pass Valve).

The rest of the differential pressure is taken in valve CBV-3.

7.1.2 With secondary pumps

Secondary pumps can be used for several reasons:

1. To compensate for large differential pressure without unnecessarily increasing the pressure head of the main pump.
2. To cancel all influences of the primary differential pressure increases on the water flow of the secondary circuit.
3. To adjust the heating water temperature in a circuit by injection to obtain a secondary constant flow, a better control, or to protect a coil against freezing.

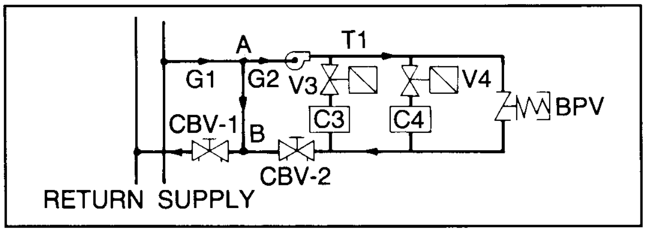


Fig. 47. Circuit with secondary pump - high primary ΔP. Secondary = primary water temperature

In Figure 47, any primary increases in ΔP have no influence on the secondary circuit. This independence is obtained with the bridge section "AB" which does not allow any differential pressure transmission in the secondary circuit.

CBV-1 is adjusted to G1 = 1.1 G2. If G1 is lower than G2 a reverse flow occurs in A-B. A becomes a mixing point and temperature T1 decreases.

For the secondary circuit, the bridge section "AB" is like a "boiler" without hydronic resistance. If the flow G1 is too large, primary pumping consumption increases, primary balancing is not reached and the differential pressure between A and B cannot be neglected.

The purpose of the BPV is to stabilize the secondary ΔP if there are long runs of pipe and to protect the pump when all control valves are closed.

Balancing procedure (Figure 47):

- Close the BPV
- Open all control valves V3-V4
- Adjust total flow G2 with CBV-2
- Open and adjust set point of BPV until we note an increase of G2
- Adjust CBV-1 to get G1 = 1.1 x G2

Figure 48 is similar to Figure 47 with control of secondary inlet water temperature.

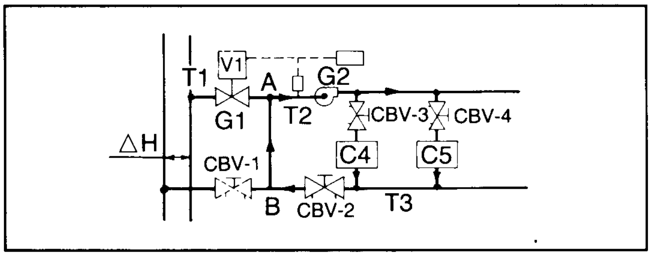


Fig. 48. Control of the secondary inlet water temperature with a high primary ΔP

Figure 48 represents a typical circuit adopted when the secondary circuit has to work with a low water temperature.

For instance, take a radiant floor heating system with T2 max = 120°F and corresponding value of T3 = 100°F. On the primary, the inlet water temperature is T1 = 200°F. As the energy furnished by the primary equals the energy consumed by the secondary, G1 x (200-100) = G2 x (120-100), then G1 = 0.2 x G2.

CBV-2 is used to balance the secondary with the CBV in series with each terminal. CBV-2 permits water flow G2 to be measured. Water flow G1 should be adjusted using CBV-1 with the motorized valve fully open.

Please note that CBV-1 decreases the authority of V1. For this reason, size V1 for at least 50% of ΔH.

Limiting the water flow G1 allows the control valve V1 to use its full stroke and avoids the risk of overheating in the secondary circuit.

Balancing procedure (Figure 48):
- Balance the secondary circuit
- Measure the water flow G2 with CBV-2
- Open V1 and adjust flow G1 = 0.2 x G2 with CBV 1

If the maximum secondary water temperature equals the primary water temperature, the flow G1 = 1.10 x G2.

If the primary pressure is large and the flow G1 small, it may be difficult to find a control valve with such a small Cv value. In this case the principle indicated on Figure 49 can be used.

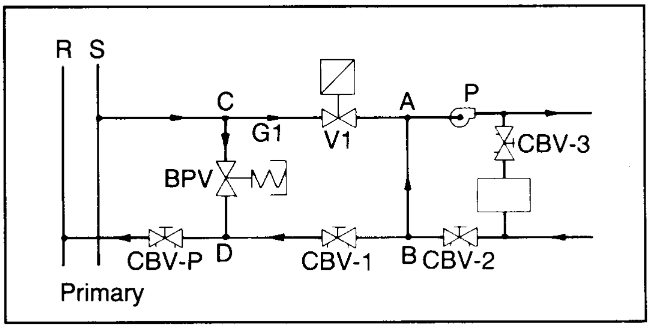


Fig. 49. Compensation of primary variable differential pressure or too large ΔP head

Balancing procedure (Figure 49):
- Shut the BPV and open V1 completely
- Adjust Cv of CBV-1 = 1.5 x G1s (G1s = G1 at design)
- Adjust the flow G1 with CBV-P to obtain G1 = 1.1G1s
- Adjust the set point of the BPV until the flow G1 in CBV-P increases by 5%.

All high pressures in the primary are taken by CBV-P and the differential pressure is maintained constant between C and D. The authority of the control valve V1 is near the value of 1.

Secondary circuit with freeze protection:
The injection principle is sometimes used with a preheating coil in contact with outdoor air. A secondary pump allows a better homogeneous leaving air temperature, improves the control and gives better freeze protection.

However, if the secondary pump stops, all primary water flow goes through the bypass AB and we take the risk of freezing the coil. In this case only a check valve CV-1 is allowed between A and B and control valve V1 is a normally open valve.

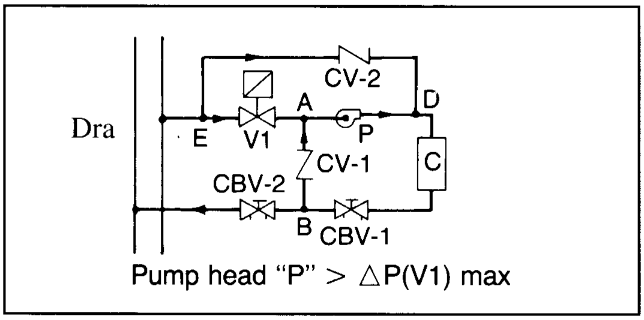


Fig. 50. Freeze protection of a preheating coil

To protect the coil when pump "P" stops with the valve V1 closed, a second check valve (CV-2) can be put between E and D. While pump P runs, the pressure in D is higher than in E and the check valve (CV-2) is closed. When the pump P stops with V1 closed, the primary water flows through CV-2 and the coil.

7.2 Three-way control valves for mixing

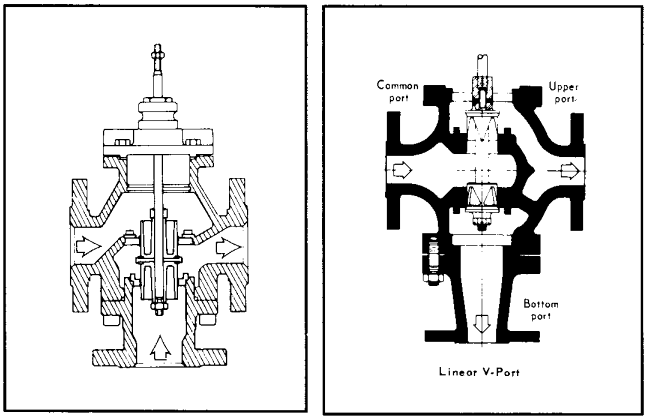


Fig. 51. Three-way mixing valve, left and three-way diverting valve, right.

Three-way mixing valves are used to adapt the temperature of a circuit to its specific requirements.

The available water temperature is constant or chosen to meet the requirements of one or more circuits.

The three-way mixing valve, at least in theory, enables a constant flow in the secondary circuit feed.

7.2.1 Zone control with mixing valve

Three-way valve representation:
When three-way control valves are symmetrical, ports A and B have the same flow characteristic and are interchangeable. However, most of the three-way valves are not symmetrical and instead should have an equal % flow characteristic on the control port and a linear flow characteristic on the bypass port. This combination reduces the variations of the total water flow when the valve's authority is near 0.5. This is true for three-way mixing or diverting valves.

This effect on the total water flow is mainly visible when the control valve is in the middle position, since a balancing valve in the bypass has design effect only when the bypass port is near the fully open position.

However, the emission characteristic depends essentially on the control port characteristic. If we use the wrong port on the control side, the result will be very bad. The danger is real since many documents represent port A mounted in the bypass, whereas others put port B in the bypass In fact, this is not important when the valves are symmetrical. To avoid confusion, we will represent the control port with a letter E or with point (*) as below (Figure 52). The common port will be represented by letter C.

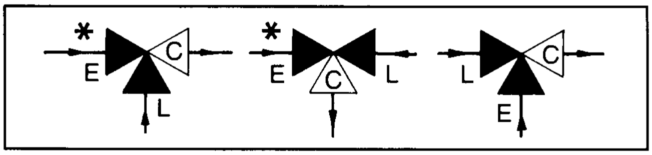


Fig. 52. Schematic symbols of three-way mixing valves with various flow patterns and characteristics (C = common port, E = control port, L = bypass port)

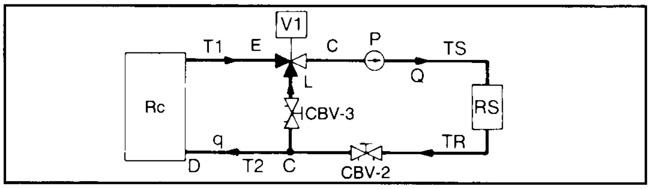


Fig. 53. Zone control with mixing three-way valve

In small systems, the boiler creates small pressure drops and there are only zone pumps in the circuits.

The three-way valve enables the feed water at temperature T1 to be mixed with the return water from the terminals at temperature TR, in order to obtain a mixture at the required temperature TS.

If port E opens, port L closes by an equivalent amount. If port E is kept closed, no energy is taken from the boiler and the return temperature TR eventually attains the mean room temperature.

It is clear that the control port is port E which controls the injection of energy in the circuit.

To preserve the characteristic of port E, its pressure drop, for the maximum water flow, must be at least equal to the pressure drop in the boiler for the same flow; this gives an authority ß = 0.5.

Generally speaking, a boiler's pressure drop is low and the three-way mixing valves are designed for a pressure drop in the order of 1 psi for maximum water flow.

$$\text{Then } Cv = \sqrt{P} \times \text{USGPM}$$

$$= \sqrt{1} \times \text{USGPM} = \frac{\text{Q BTU/hr}}{500 \times \Delta T}$$

This should not be taken as gospel since certain boilers have high pressure drops and the generator may be a heat exchanger or a heat pump with a pressure drop sometimes exceeding 5 psi. In such a case, it is best to compensate the pressure drop of the boiler with a primary pump. (See Figure 27.)

Do we need a balancing valve CBV-3 in the bypass?

The water flow coming from the terminals in point B can flow through sections BL or DB. If the pressure drop in the generator is large, the majority of the water flow has a tendency to go through BL and the three-way valve must maintain port L near the closed position to obtain some water flow through the boiler. This situation does not allow the control valve to work on its full stroke and may produce hunting. To avoid this situation, we can put a balancing valve CBV-3 in the bypass to create the same hydronic resistance as the boiler.

Balancing procedure (Figure 53):
- Open completely port E of the control valve and measure the water flow through CBV-2.
- Open completely port L of the control valve and adjust the balancing valve CBV-3 to obtain the same water flow through CBV-2 that was measured during the first step.

In practice, the flow characteristic of the control valve is better without balancing valve CBV-3, particularly when the valve's authority is small. When port L is near the open position, the total secondary water flow has a tendency to increase because the hydronic resistance between C and L is small. The pressure drop in the terminal RS increases and the pressure in C decreases. It is this pressure in C which pushes the water through RC and port E and the water flow is smaller than normal, giving a better control of the emission for small loads.

The second problem which may justify CBV-3 is the influence of valve V1 on the secondary water flow. When port L is open and without any hydronic resistance between B and L, the secondary water flow can increase too much.

In general, the pressure drops of the control mixing valve and the boiler are small in comparison with the head of the secondary pump and their modifications have no significant influence on the total secondary water flow.

7.2.2 Three-way mixing valves with a primary and secondary pump

In some large installations, the circuits are connected to a header loop. The available differential pressure H is determined by the pressure drop across valve V4 (Figure 54). The configuration involves a certain number of risks.

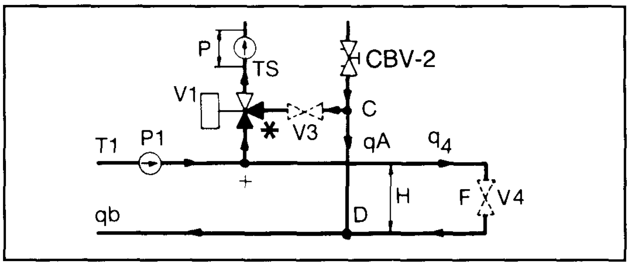


Fig. 54. Mixing valve connected to an active header

When the three-way valve is fully open (100% flow through control port *) the header pressure H is put in series with the pressure P of the circuit circulator, and the water flow increases.

Balancing valve CBV-3 should certainly not be installed, since there is no need to restrict the flow in the bypass. Note, in fact, that D is at a lower pressure and tends to draw the water flow from point C.

However, the most dangerous effect results from the distortion of the working characteristic of the three-way valve; the differential pressure H tends to increase the flow in the control port and to reduce the water flow in the bypass. We can even attain TS = T1, cancelling the water flow in the bypass before the control port is fully open.

This problem is avoided with a design as shown in Figure 55. An equalizer bridge DE does not allow the primary differential pressure to be transmitted to the secondary circuit. The three-way valve sees this bridge like a "boiler" with no pressure drop and works with an authority ß near a value of 1.0. The balancing valve CBV-2 compensates the pressure head H.

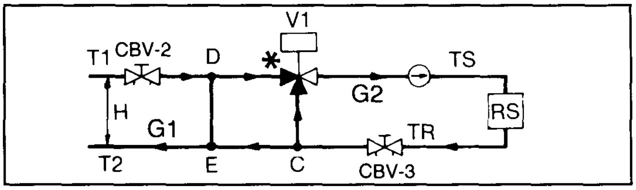


Fig. 55. Compensating primary pressure at a mixing valve.

Balancing procedure (Figure 55).

- Measure or adjust the secondary water flow G2 with CBV-3
- Adjust the primary water flow G1 = 1.1 x G2 with CBV-2

It means that Cv (CBV-2)

$$= 1.51 \times 1.1 \times \frac{G2}{\sqrt{H(Ft)}}$$

The primary water flow (valve CBV-2) has to be adjusted for a flow approximately 10% larger than the secondary water flow (valve CBV-3) to provide a positive circulation from D to E.

If the primary flow through valve CBV-2 cannot be adjusted for 10% greater than secondary flow through CBV-3, then the flow will be reversed in the bridge D-E to cause a lower supply water temperature to valve V1 causing lower coil output. To correct this, reduce valve CBV-3 to 90% of the actual flow through valve CBV-2.

If the primary water temperature is constant, the control port of the three-way valve should have an equal percentage flow characteristic. However, if the primary water temperature T1 is reset with the outdoor temperature, the control valve V1 may be a linear symmetrical valve.

7.2.3 Mixing three-way valves in the mechanical room

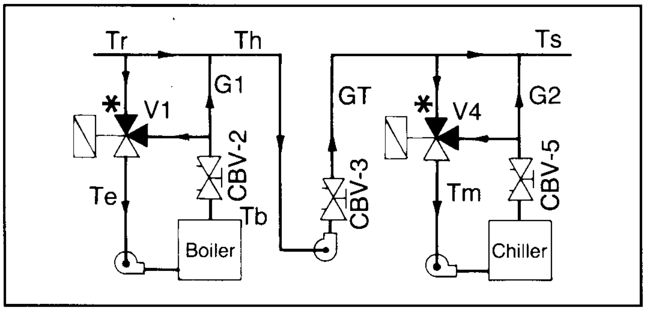


Fig. 56. Mixing three-way valves in the mechanical room

Figure 56 represents a configuration used in a two-pipe HW-CW system.

In winter, the control valve V1 controls the water flow G1 injected in the main to obtain the required temperature Th depending on the outdoor temperature. At the same time, the control valve V1 does not allow the water temperature Te to be lower than a certain value in order to protect the boiler against corrosion and thermal shock.

If we call GT the water flow in the main and G1 the maximum water flow coming from the boiler, the maximum water temperature Th can be obtained:

$$Th\ max = Tr + \frac{G1}{GT}\ (Tb - Tr)$$

If this maximum temperature has to be equal to the max boiler water temperature Tb, G1 max must be equal or more than GT. Balancing valve CBV-2 makes it possible to adjust or to check the boiler's water flow in comparison with the total water flow measured with the balancing valve CBV-3. The CBV-3 serves during the entire balancing of the building.

Control valve V4 prevents too high a water temperature Tm from entering the chiller. Similarly the chiller water flow has to be adjusted or controlled with a balancing valve CBV-5.

7.3 Three-way diverting control valves

We have said that the control of a water flow using a two-way control valve obviously causes disturbances transmitted into the primary circuit, which has an essentially variable water flow.

Problems could occur with the dynamic balancing both on flow and temperature.

Those disadvantages can be reduced or eliminated if the two-way control valves are replaced with three-way diverting valves as shown in Figure 57.

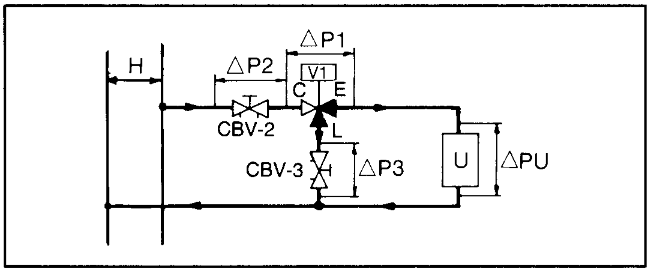


Fig. 57. Diverting circuit using a diverting three-way valve

E is the regulating port which controls the feed water flow of terminal U; port L derives the difference in the return of the primary circuit whose water flow is thus theoretically kept constant.

$$\text{The valve's authority } \beta = \frac{\Delta P1}{\Delta P1 + \Delta Pu}$$

must be equal or larger than 0.5, so ΔP1 equals at least ΔPu for the maximum water flow.

Port E has the characteristic that would have been chosen if a two-way control valve had been used; it is generally an equal percentage type.

Since the purpose of the three-way diverting valve is to maintain a constant primary water flow so as to avoid hydraulic interferences with the other circuits, it is only logical to ensure that this aim is in fact realized.

To do this, a balancing valve CBV-3 is fitted in the bypass to create a pressure drop equivalent to the terminal for the maximum water flow. In this way, if port E or port L is fully open, the primary flow is unchanged because the hydraulic resistances in series with each port are the same.

Balancing valve CBV-2 enables constant primary water flow and hence the maximum secondary water flow to be set to the desired value.

Valve CBV-2 does not affect the authority of the three-way valve because it carries a constant flow and adjusts the feed pressure to the required constant value.

This remark is extremely important because it shows that the differential pressure can be adjusted according to the Cv value of the control valve without changing its authority; this is not directly possible with a two-way control valve.

Balancing Procedure:
- Open port E completely
- Set valve CBV-2 to obtain the desired water flow G
- Open port L completely
- Set valve CBV-3 to obtain through CBV-2 the same water flow G

Note:
Three-way valves are generally designed to operate as mixers. If they are used in a diverting circuit, as in Figure 57, the water circulates in the opposite direction these valves are designed for, unless diverting bodies are specified. Reversing the direction may lead to a substantial increase in the noise level and to valve chatter.

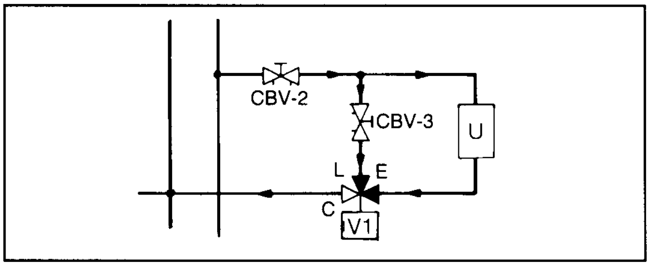


Fig. 58. Diverting circuit using a mixing three-way valve

For this reason the diverting function using a three-way mixing valve is obtained by fitting it in the return circuit as shown in Figure 58. The same function is obtained while keeping the correct direction of water circulation in the valve.

7.4 Is it always necessary to balance the bypass?

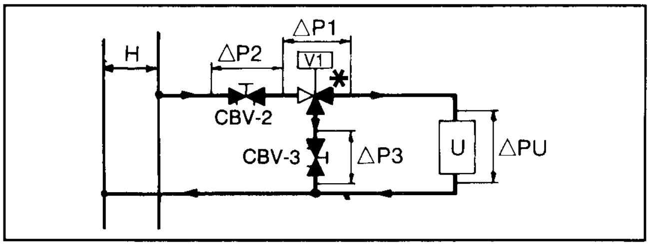


Fig. 59. Three-way diverting valve

We call ΔPu the calculated pressure drop in the terminal in percentage of the total head H available on the branch. The valve CBV-2 is installed and adjusted.

Without balancing valve CBV-3, the maximum water flow obtained when the valve's port on the bypass is fully open is given by:

$$\text{GT max \%} = \frac{1000}{\sqrt{100 - \Delta Pu}}$$

The maximum water flow depends on ΔPu according to the following table:

ΔPu %	GTmax %	ΔG %
17	110	+ 10
30	120	+ 20
40	130	+ 30
50	141	+ 41
60	158	+ 58
70	182	+ 82
80	223	+ 123

When ΔPu is small, the excess pressure is taken in the control valve and/or the balancing valve CBV-2 which reduces the variations of the total water flow.

If we accept as the limit an increase of the water flow of 20%, the balancing valve CBV-3 is not needed when Pu is lower than 30% of the total head H.

Don't forget that the balancing valve CBV-2 is always necessary.

However, the total water flow decreases when the three-way valve is near its middle position and the value obtained does not depend on balancing valve CBV-3.

7.5 Is it true that a three-way diverting valve not balanced in the bypass has a better emission characteristic? (Per Figure 59)

Small loads are the most difficult to manage. This difficulty increases under the following conditions:

- Small design water temperature drop ΔTs
- Small rangeability of the control valve
- Small authority of the control valve
- Control port of the three-way valve does not have an equal percentage characteristic
- Small pressure drop in balancing valve CBV-2
- It does not depend on the characteristic of the bypass port

Normally the presence or omission of balancing valve CBV-3 has practically no influence on the emission, with an exception made for a very low valve authority. The following table is an example of this:

Valve rangeability = 30		Minimum emission controllable in % of max load			
		ΔTs = 20F		ΔTs = 60F	
		Bypass balanced		Bypass balanced	
ß authority	CBV-2%*)	YES	NO	YES	NO
0.25	0	40	40	19	19
	20	40	35	18	15
	40	40	31	18	13
	60	40	29	18	12
0.50	0	32	32	14	14
	20	32	30	14	13
	40	32	29	13	12
	60	32	27	13	11
0.75	0	28	28	11	11
	20	28	27	11	11
	40	28	27	11	11
	60	28	26	11	10

(*) CBV-2 in % represents the pressure drop in the balancing valve CBV-2 in % of H.

Results obtained on the control side depend on the several factors; poor selections can give poor results.

Figure 60 and 61 show good and poor choices.

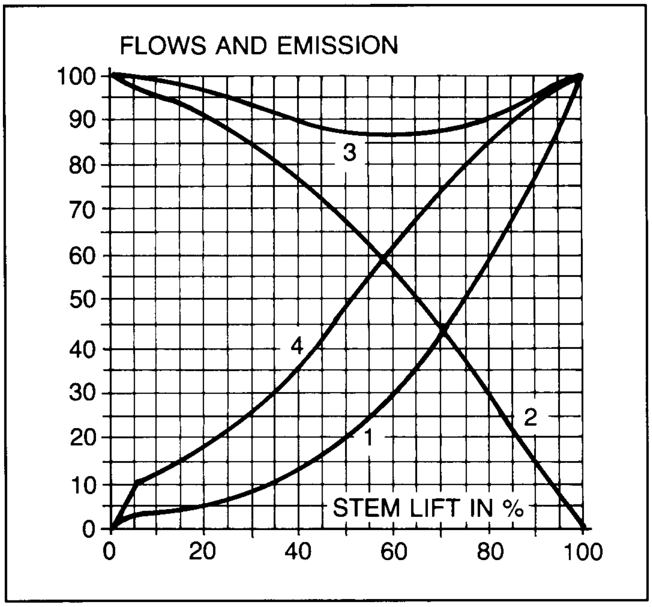


Fig. 60. The good choice

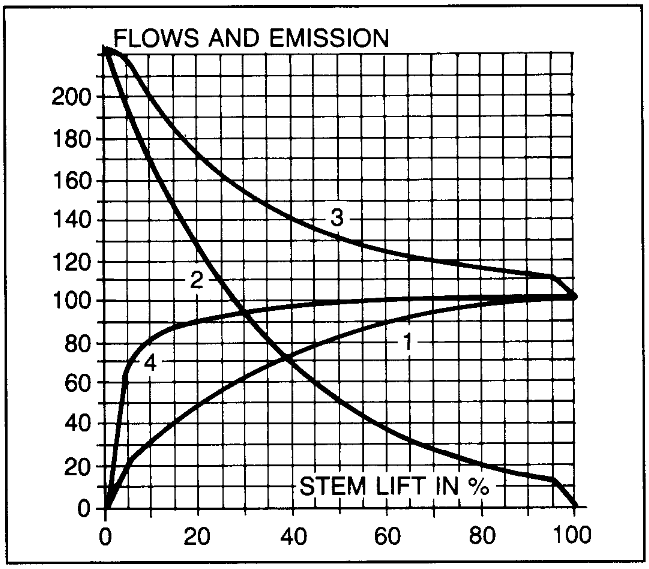


Fig. 61. The poor choice
1 - Water flow in the terminal; 2 - Water flow in the bypass
3 - Total water flow ; 4 - Terminal emission with
EWT = 200°F

7.6 Three-way valve mounted in an injection circuit

In Figure 62, a three-way mixing valve mounted in an injection circuit is shown.

The principle illustrated in this figure is commonly used in radiant floor heating systems with a temperature TS lower than the supply water temperature T1.

However, the same system can be used to work with TSmax = T1.

Some advantages of this circuit are the following:
- Constant water flow on the primary side
- Constant water flow on the secondary side
- Valve's authority = 1
- No balancing valve required in the bypass
- Ability to work with low temperature on the secondary

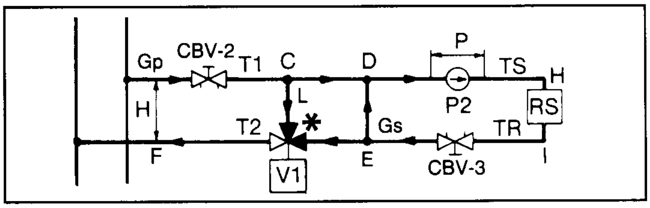


Fig. 62. Injection circuit with three-way valve

The primary water, at temperature T1, and circuit return water at temperature TR, are mixed at point D.

The primary and secondary circuits are separated by the short circuit branch or bridge DE.

The pressure head H only has to overcome the pressure drops of valves V1 and CBV-2 and pipes GCLF.

The two water flows Gp in the primary and Gs in the secondary vary as follows:

$$Gp = Gs \times \frac{(TS\ max - TR\ max)}{(T1 - TR\ max)}$$

If TSmax = T1, then Gp = Gs

Balancing procedure (Figure 62):
- Adjust and/or measure the secondary water flow Gs
- Open completely valve V1 on bypass port
- Adjust the flow Gp according to value calculated above with formula.

7.7 Glycol correction

When using a certain proportion of glycol in water, the pressure drop in the pipe calculated for a normal water temperature of 68°F (20°C) is multiplied by a coefficient KPD.

Moreover, the water flow indicated by the COMPUFLO Meter has to be corrected; the real value equals the indicated value in USGPM multiplied by a factor KG.

USGPM (actual) = USGPM (tested) x KG

For pipe with a rugosity of 0.05 mm (0.002") the coefficient of correction KPD is estimated by the following formula (turbulent condition).

$\mathrm{KPD} = d \times V^{0.13}$

with d = density of the liquid

V = viscosity in centistokes

For a valve with a turbulent condition the factor $\mathrm{KG} = d^{-0.5}$

1. Conversion of viscosity units

Centistokes	1	4	7	10	15	20	25	30	40	60
°ENGLER	1	1.3	1.6	1.0	2.3	2.9	3.4	4.1	5.4	7.0
Redwood sec	28	35	43	52	68	86	105	125	164	245
Saybold sec		39	49	59	77	97	119	141	186	277
SAE Nr									20	30

2. Correction table for water + ethylene glycol

C% = weight proportion of glycol in %

d = density

V = viscosity in centistokes

°F	40				70				180			
°C	4.5				21				82			
C%	d	V	KPD	KG	d	V	KPD	KG	d	V	KPD	KG
0	1.	1.53	1.06	1.00	1.	1.	1.	1.	0.97	0.36	0.85	1.01
10	1.02	2.02	1.11	0.99	1.01	1.29	1.05	0.99	0.98	0.43	0.88	1.01
20	1.03	2.66	1.17	0.99	1.03	1.67	1.10	0.99	0.99	0.53	0.91	1.00
30	1.05	3.50	1.23	0.98	1.04	2.16	1.15	0.98	1.00	0.64	0.95	1.00
40	1.06	4.62	1.29	0.97	1.06	2.80	1.21	0.97	1.01	0.78	0.98	0.99
50	1.08	6.09	1.36	0.96	1.07	3.63	1.26	0.97	1.02	0.94	1.02	0.99

3. Correction table for water + propylene glycol

°F	40				70				180			
°C	4.5				21				82			
C%	d	V	KPD	KG	d	V	KPD	KG	d	V	KPD	KG
0	1.	1.53	1.06	1.00	1.	1.	1.	1.	0.97	0.36	0.85	1.01
10	1.01	1.97	1.10	0.99	1.01	1.47	1.06	0.99	0.98	0.46	0.88	1.01
20	1.02	3.01	1.18	0.99	1.02	2.16	1.13	0.99	0.98	0.57	0.91	1.01
30	1.03	4.61	1.26	0.99	1.03	3.17	1.20	0.99	0.98	0.71	0.94	1.01
40	1.05	7.06	1.35	0.98	1.04	4.66	1.27	0.98	0.99	0.88	0.97	1.00
50	1.06	10.8	1.44	0.97	1.05	6.84	1.35	0.98	0.99	1.09	1.00	1.00

Example:

Water at 41°F with 50% propylene glycol creates a supplementary pressure drop in the pipe of 44% (KPD = 1.44). The real value of water is the value indicated by the COMPUFLO Meter multiplied by KG = 0.97.

4. Correction of water flow for bigger viscosity, small Cv and DP.

It can happen that the flow is not turbulent.

In this case, the water flow indicated by the COMPUFLO Meter is multiplied by KG and by another coefficient, FR.

Values of FR depend on a parameter A according to the following table:

$$A = \frac{\mathrm{Cv} \times \Delta P(\mathrm{Ft})}{d \times V^{2} \times 38.8} \times 10^{6}$$

$$= \frac{\mathrm{Kv} \times \Delta P(\mathrm{bar})}{d \times V^{2}} \times 10^{6}$$

A	195000	16000	3520	1170	466	203	94	44	21	10	5	4.3
FR	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45

Example:
We take the same example as above. With the Cv value of 2 and a $\Delta P = 1.5$ FT, the indication of the COMPUFLO corresponds to 1.62 USGPM.

$$\text{Parameter A} = \frac{2 \times 1.5 \times 10^{6}}{1.06 \times (10.82)^{2} \times 38.8} = 623$$

KG = 0.97 and FR = 0.82
Then USGPM = 1.62 x 0.97 x 0.82 = 1.29

This correction is an approximation since it is normally used for valves fully open and a valve section which corresponds with pipe diameter.

Formula used is the following:
With $Z = 6 \times A^{(1/6)}$
For $Z > 0.8$ $FR = 1 - e^{-1.034(z-0.114)}$
For $Z < 0.8$ $FR = Z^3$

7.8 Technology of Balancing Hydronic Systems; Conclusion

The subject of balancing valves has only been touched.

The main aim is to show that the use of Armstrong Balancing Valves is not limited to adjusting the flows of mains and branches.

Balancing valves can solve many problems found in hydronic systems. Combining them with control valves is only a limited sample and we have only considered a few aspects of these combinations.

Hydronic balancing of a heating/cooling system ensures that it is uniform, giving ideal running conditions.

Flow limiting ensures an even distribution of energy and enables zone control valves to compensate for the flow of internal disturbances.

Hydronic balancing is possible when appropriate means are provided; these include Armstrong CBV Balancing Valves, COMPUFLO measuring instruments and reliable methods.

The energy savings made by hydronic balancing depend on many factors. If a system is already properly balanced, no increased benefit can be expected from additional balancing. However, the Armstrong Balancing Valve can be used to measure the actual flow conditions to check the system operating conditions.

Our experience is that most systems are not properly balanced. Adjusting the water flows in the risers can give spectacular results, with the reduction of energy consumption providing a payback in less than one season.

Hydronic balancing is an operation of fundamental importance to ensure proper system operation, to achieve energy savings, and to enable the application of other sophisticated controls and optimization techniques.

Building designers, owners, and managers should become aware of the economic savings of a well balanced hydronic system for their existing or future buildings. And their economic analysis should take into account both energy savings and the financial aspects of attracting and keeping tenants who are happy with the comfort of their home or office.