BUILDING ENERGY MANAGEMENT AND REDESIGN RETROFIT (BEMARR)

CHILLER SYSTEMS

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1. GENERAL

1.01 In the past, multiple chilled water machines were often piped in parallel as shown in Fig. 1. Each machine was controlled to produce the required chilled water discharge temperature. This application works well when the system load is relatively constant and both chillers are required to produce system capacity, but it tends to waste energy under partial loads. There are two alternate solutions which can provide net power savings.

(a) Piping chillers in series

(b) Utilizing variable volume chilled water systems.

The material used in this section has been extracted from the *Building Energy Management and Redesign Retrofit (BEMARR) Manual,* issued with GL-76-10-077 (EL-4857), dated October 7, 1976.

1.02 Whenever this section is reissued, the reason(s) for reissue will be listed in this paragraph.

2. APPLICATION

A. Series Piping of Chillers

2.01 For this alternative, consider two 284-ton capacity chillers, as shown in Fig. 1, piped in parallel. The chilled water temperatures are 42°F supply and 58°F return. Based on manufacturers' data and available design information, the kilowatts per ton at full load is 0.85.

2.02 Now consider piping the chillers in series and have each chiller cool 100 percent of the circulated water quantity through one-half of the required temperature range (Fig. 2). Under these conditions, based on manufacturers' data, the kilowatts of power input per ton of refrigeration decreases to 0.78 kilowatts per ton. Because each machine is operating at a lower temperature differential, they will use less power. For this example, repiping and modifying control settings will result in approximately 8 percent energy savings at peak design load conditions.

2.03 Control is also simplified, especially at part load. When two chillers operate on a parallel system, a potentially troublesome mixing problem occurs. It is most critical at half-system load when one chiller is turned off (Fig. 3). Return water is unprocessed as it passes through the "off" chiller, and the operating machine must overchill to meet the mixed water temperature demanded by the system controls.

2.04 Again, observe how mixing causes energy waste. But worse, the operating chiller may be physically unable to make water cold enough to satisfy the controls. With a series-flow configuration, however, if chiller A is off, chiller B can still produce the required water temperatures without overchilling.

B. Variable Volume Chilled-Water Systems

2.05 The second alternative is variable water flow systems. This is analogous to a variable air volume system. By installing a bypass or cross-connection between the chilled water supply and return piping, the chilled water system can be separated into primary and secondary piping loops which can operate as a variable volume water system (Fig. 4).

2.06 The secondary water loop is variable flow. Secondary water flow is varied as the flow demand is reduced through 2-way valves controlling water flow through the system cooling coils. This will produce savings in secondary pumping power. See Section 760-570-400.*

2.07 Primary loop water flow is relatively constant. The quantity of water flow through the primary loop is the sum of the flows through each operating chiller-pump combination. Each chiller has a dedicated or individual pump.

2.08 Additional power can be saved by matching primary flow with the reduced secondary demand. When a reduction in the cooling load occurs, the 2-way control valves at the terminal units close and chilled water overflow will be in the "A" direction of the bypass. (See Fig. 4.) The amount of overflow in the "A" direction indicates the potential for turning off chillers and pumps. If the overflow rate (sensed by the differential flow switch) exceeds one chiller-pump capacity, there is no reason to keep it running. There is no mixing problem because no water flows through any of the inoperative chillers since their individual pumps are turned off and automatic control valves are closed.

2.09 As the primary loop flow adjusts to the secondary requirements, the system will use only enough power to meet the diversified demands of the water coils. Even the secondary loop design flow is less because the total flow is based on average load rather than maximum connected load. See Section 760-570-400.

*Check Divisional Index 760 for availability.

2.10 When an increase in the cooling load occurs, there is an increase in the flow demand as the 2-way control valves at the terminal units open. Flow in the primary bypass loop is the key. If secondary flow demand exceeds the primary flow being supplied, water will flow in the "B" direction through the bypass (Fig. 4). The differential flow switch detects this flow direction and signals another chiller-pump combination to start. Primary chilled water flow, therefore, is matched to the requirements of the secondary loop.

2.11 Not only does this arrangement save pumping power, it also simplifies a complex control problem of staging chillers on and off. Further, any number of chiller-pump combinations can be used in the original design or added in the future. This arrangement is very versatile as chillers can be of any type, manufacturer, or size.

3. ECONOMIC ANALYSIS

3.01 The main purpose of these piping configurations is to save refrigeration energy used in overchilling and pump energy used in bypassing water through unused chillers. The amount of pumping energy saved is discussed in Section 760-570-400.

3.02 To calculate the energy saved over the entire refrigeration season by not overchilling with a parallel pipe chiller system (Fig. 3), use the following data and refer to Table A.

(a) Water temperature differential at design = 16°F.

(b) Required supply water temperature = 42°F.

(c) Two 50-ton chiller machines piped in parallel.

(d) Gallons per minute (GPM) of chilled water pump = 150, with 75 GPM through each chiller.

3.03 The chilled water flow rate (GPM) required to remove a given cooling load is dependent upon the temperature differential (ΔT) maintained between the chilled water supply and return temperatures and is determined from the following equation:

$$\text{GPM} = \frac{\text{BIN MBH} \times 1000\ \text{BTU/MBH}}{\Delta T \times 500}$$

For a given chilled water flow rate (GPM) and cooling load [1000 British Thermal Units per hour (MBH)], the temperature differential [ΔT (°F)] required between the chilled water supply and return is therefore:

$$\Delta T = \frac{\text{BIN MBH} \times 1000\ \text{BTU/MBH}}{\text{GPM} \times 500}$$

3.04 The temperature differentials required for each temperature BIN (Table A) at the given flow rate of 150 GPM, for this example, are shown in Table B. For example, temperature BIN E has a cooling load of 875 MBH and the temperature differential required to remove this quantity of heat is:

$$\Delta T = \frac{875\ \text{MBH} \times 1000\ \text{BTU/MBH}}{150\ \text{GPM} \times 500}$$

$$\Delta T = 11.7°\text{F}$$

In absorbing the 875-MBH cooling load, the chilled water will be heated as it is pumped through the cooling coil. The resulting temperature is the return water temperature to the chillers:

Return water temperature

$= 42°\text{F} + 11.7°\text{F}$

$= 53.7°\text{F}$

3.05 As shown in Table A, both chillers (Fig. 3) are required to handle the cooling loads in temperature BINs B through G. These cooling loads are greater than the 600-MBH capacity of one chiller which is 50 tons. Only one chiller is required for the loads in temperature BINs H through M or those cooling loads less than the 600 MBH.

3.06 Even though the temperature differential required across the cooling coil in temperature BIN H is less than half of that temperature differential required for temperature BIN B (7.5°F verus 16°F), 42°F chilled water is required for loads in BINs H through M. This is a function of the coil design. When only one chiller is operating, the 42°F chilled water supply temperature is actually the mixed chilled water temperature of that water supplied by both the operating chiller (Chiller A) and the idle chiller (Chiller B). The problem, then, is at what temperature should chilled water be supplied from Chiller A so that the resultant mixture of chilled water supply is 42°F or:

Mixed Chilled Water Supply Temperature (MCWST) = 42°F

$$\text{MCWST} = \%\text{GPM}_A\,(\text{DT}_A) + \%\text{GPM}_B\,(\text{DT}_B) + \ldots\%\text{GPM}_X\,(\text{DT}_X)$$

where:

$\%\text{GPM}_A$ = percentage of total system flow rate through Chiller A

DT_A = discharge temperature of chilled water from Chiller A

$\%\text{GPM}_B$ = percentage of total system flow rate through Chiller B

DT_B = discharge temperature of chilled water from Chiller B

$\%\text{GPM}_X$ = percentage of total system flow rate through last chiller of system

DT_X = discharge temperature of chilled water from last chiller of system.

In this example, the flow rate through each chiller is 50 percent of the total system water flow; therefore, the above equation reduces to:

$$\text{MCWST} = \frac{50}{100}(\text{DT}_A) + \frac{50}{100}(\text{DT}_B)$$

$$42°\text{F} = 0.5\ \text{DT}_A + 0.5\ \text{DT}_B$$

Using data from temperature BIN H, the discharge temperature (DT_B) of the idle chiller (Chiller B) is equal to the return water temperature or 49.5°F. The discharge temperature TD_A for the operating chiller (Chiller A) can be calculated:

$$DT_A = \frac{42°F - 0.5\ (49.5°F)}{0.5}$$

$$DT_A = 34.5°F$$

3.07 At cooling loads greater than 600 MBH (temperature BINs G through B in Table A), both chillers are required and no overchilling results. However, at cooling loads less than 600 MBH (temperature BINs H through M in Table A) when only one chiller is required, overchilling results and energy is wasted since only 50 percent of the water is chilled. The savings available by not overchilling can be calculated, per temperature BIN, as follows:

$$\%\ \text{savings} = \frac{\Delta T_1 - \Delta T_2}{\Delta T_1} \times 100$$

Where:

ΔT_1 = Temperature difference between the ***return chilled water*** and the ***operating chiller discharge temperature***.

ΔT_2 = Required temperature differential per temperature BIN, see Table B.

For example, using the data in Table B, the percent savings available for temperature BIN H is:

$$\%\ \text{savings} = \frac{(49.5°F - 34.5°F)}{(49.5°F - 34.5°F)} - 7.5 \times 100$$

$$= 50\%$$

3.08 Solving this equation (with the data from Table B), for all BINs with only one of the two chillers operating (BINs H through M), yields the following energy savings:

BIN	PERCENT SAVINGS
H	50
I	50
J	50
K	50
L	50
M	50

3.09 A temperature differential that is twice that actually required for all loads 50 percent and less with only one chiller operating must be used. In a system operating with this type of chilled water mixing action, the cost of cooling the loads in each temperature BIN (H through M) is twice as high as it should be.

3.10 For this example, the percent annual savings available (by eliminating the costly overchilling and mixing problem) can be calculated as follows:

$$\%\ \text{annual savings} = \frac{\text{total actual cooling} - \text{total cooling required}}{\text{total actual cooling}} \times 100$$

Where (Table A):

Total Actual Cooling = Total cooling load in BINs B through G plus twice cooling load in BINs H through M.
Total Cooling Required = Total cooling load in BINs B through M.

$$\%\ \text{annual savings} = \frac{916,895 + 2\ (1,182,930) - 2,099,825}{916,895 + 2,365,860} \times 100$$

$$= 36\%$$

3.11 In a 2-chiller installation, it is obvious that the approximate savings in energy will be 50 percent by turning off one chiller when not required. This same analysis can be applied to a multiple chiller installation with three or more chillers and with varying capacities and flow rates. For example, consider the same temperature BIN cooling loads and GPM flow rate but with three chillers in parallel:

Chiller 1 capacity = 480 MBH, 60 GPM flow rate

Chiller 2 capacity = 360 MBH, 45 GPM flow rate

Chiller 3 capacity = 360 MBH, 45 GPM flow rate.

3.12 For this example, the cooling load in temperature BIN G will be used. Chillers 2 and 3 are operating while Chiller 1 is idle.

Calculate the mixed chilled water supply temperature:

$$\text{MCWST} = \%\text{GPM}_1\ (\text{DT}_1) + \%\text{GPM}_2\ (\text{DT}_2) + \%\text{GPM}_3\ (\text{DT}_3)$$

DT_1 is the discharge temperature from Chiller 1 which equals the return water temperature from Table B for BIN G = 50.9°F

The solution for discharge temperature from Chiller 2 (DT_2) and Chiller 3 (DT_3) is:

$$42 = \frac{60}{150}(50.9) + \frac{45}{150}(\text{DT}_2) + \frac{45}{150}(\text{DT}_3)$$

$$\text{let DT}_2 = \text{DT}_3$$

$$42 = 20.36 + 0.6\ \text{DT}_2$$

$$\text{DT}_2 = \text{DT}_3 = 36.1°\text{F}$$

3.13 For this example, the percent savings available by not overchilling due to the mixing is calculated for temperature BIN G as follows:

$$\%\ \text{savings} = \frac{\Delta T_1 - \Delta T_2}{\Delta T_1} \times 100$$

where:

$$\Delta T_1 = 50.9 - 36.1 = 14.8$$

$$\Delta T_2 = 8.9$$

$$\%\ \text{savings} = \frac{14.8 - 8.9}{14.8} \times 100$$

$$= 39.8\%$$

3.14 The percent savings available can be similarly calculated for the other temperature BINs. It should be noted that varying size chillers will give greater flexibility in matching chiller(s) capacity to the load.

3.15 If for example, Chillers 1 and 2 were cooling the load in temperature BIN G with Chiller 3 idle, what would be the percent savings by not overchilling? The solution for the chilled water discharge temperatures from Chillers 1 and 2 is:

$$\text{MCWST} = \%\text{GPM}_1\ (\text{DT}_1) + \%\text{GPM}_2\ (\text{DT}_2) + \%\ \text{GPM}_3\ (\text{DT}_3)$$

$$\text{DT}_1 = \text{DT}_2$$

$$\text{DT}_3 = 50.9$$

$$42 = \frac{60}{150}(\text{DT}_1) + \frac{45}{150}(\text{DT}_1) + \frac{45}{150}(50.9)$$

Therefore

$$\text{DT}_1 = \text{DT}_2 = 38.2°\text{F}$$

The calculated percent savings available is:

$$\%\ \text{savings} = \frac{\Delta T_1 - \Delta T_2}{\Delta T_1} \times 100$$

where:

$$\Delta T_1 = 50.9 - 38.2 = 12.7$$

$$\Delta T_2 = 8.9$$

$$\%\ \text{savings} = \frac{12.7 - 8.9}{12.7}$$

$$= 29.9\%$$

3.16 Given these savings and the cost to modify the systems to eliminate the overchilling problem, life-cycle costing will determine the feasibility of the project.

TABLE A

BIN DATA—TOTAL COOLING REQUIRED

BIN	BIN TEMP RANGE	HOURS IN BIN	COOLING MBH	TOTAL COOLING REQD IN BIN MBTU
B	99/95	3	1,190	3,270
C	94/90	26	1,085	28,210
D	89/85	87	980	85,210
E	84/80	198	875	173,250
F	79/75	369	770	284,130
G	74/70	515	665	342,475
H	69/65	656	560	367,360
I	64/60	716	455	325,780
J	59/55	683	350	239,050
K	54/50	607	245	148,715
L	49/45	578	140	80,920
M	44/40	603	35	21,105
			Total	2,099,475

TABLE B

CHILLED WATER—TEMPERATURE DIFFERENTIALS

BIN	ΔT REQUIRED °F	42°F + ΔT (RETURN TEMP) °F
B	16	58
C	14.5	56.5
D	13.1	55.1
E	11.7	53.7
F	10.3	52.3
G	8.9	50.9
H	7.5	49.5
I	6.1	48.1
J	4.7	47.7
K	3.3	45.3
L	1.9	43.9
M	.5	42.5

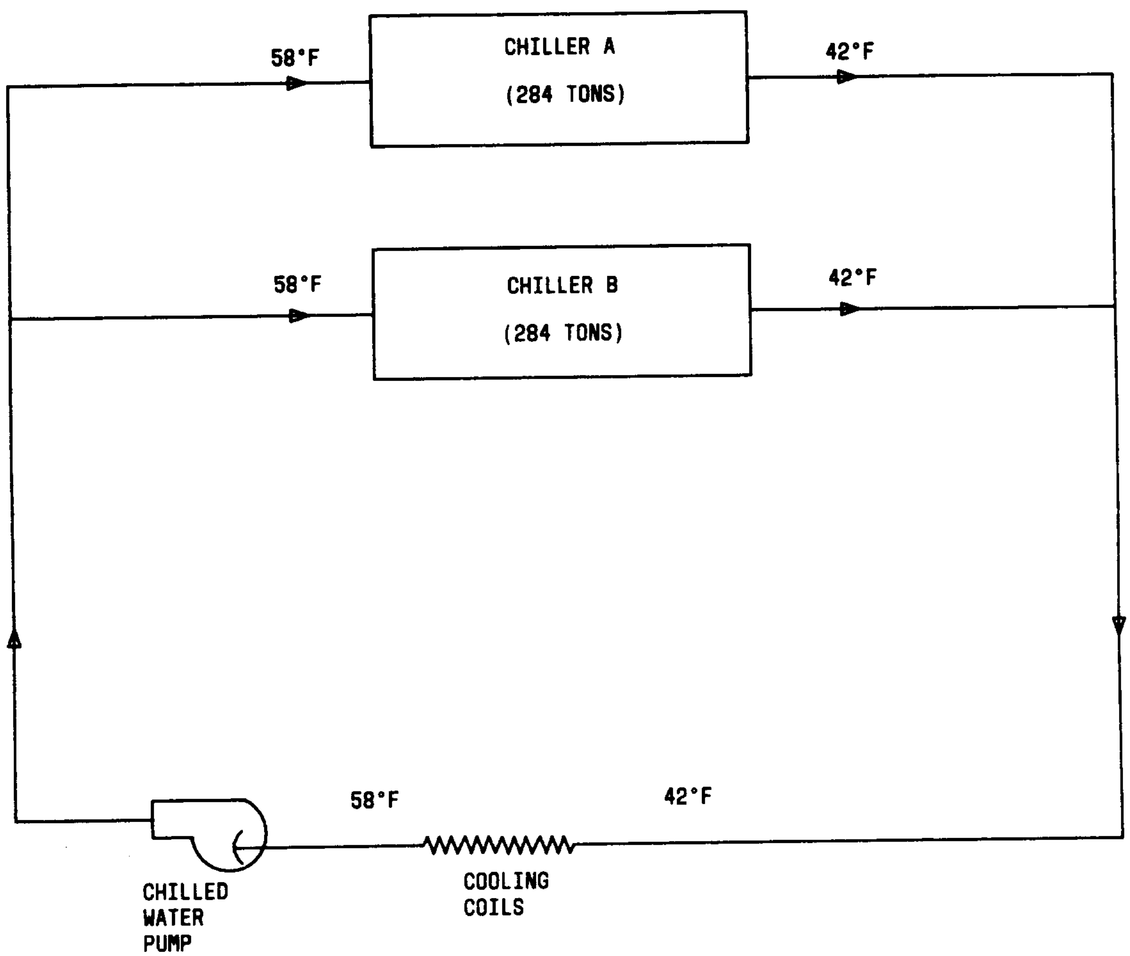

Fig. 1—Typical Parallel Piping in Chiller Systems

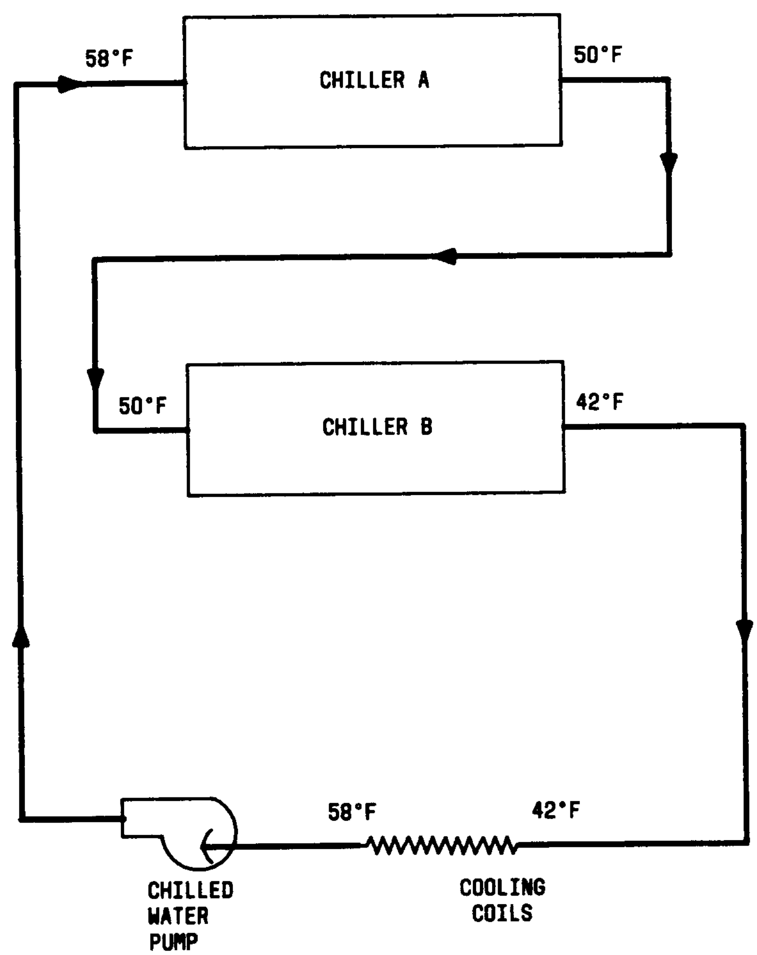

Fig. 2—Typical Series Piping in Chiller Systems

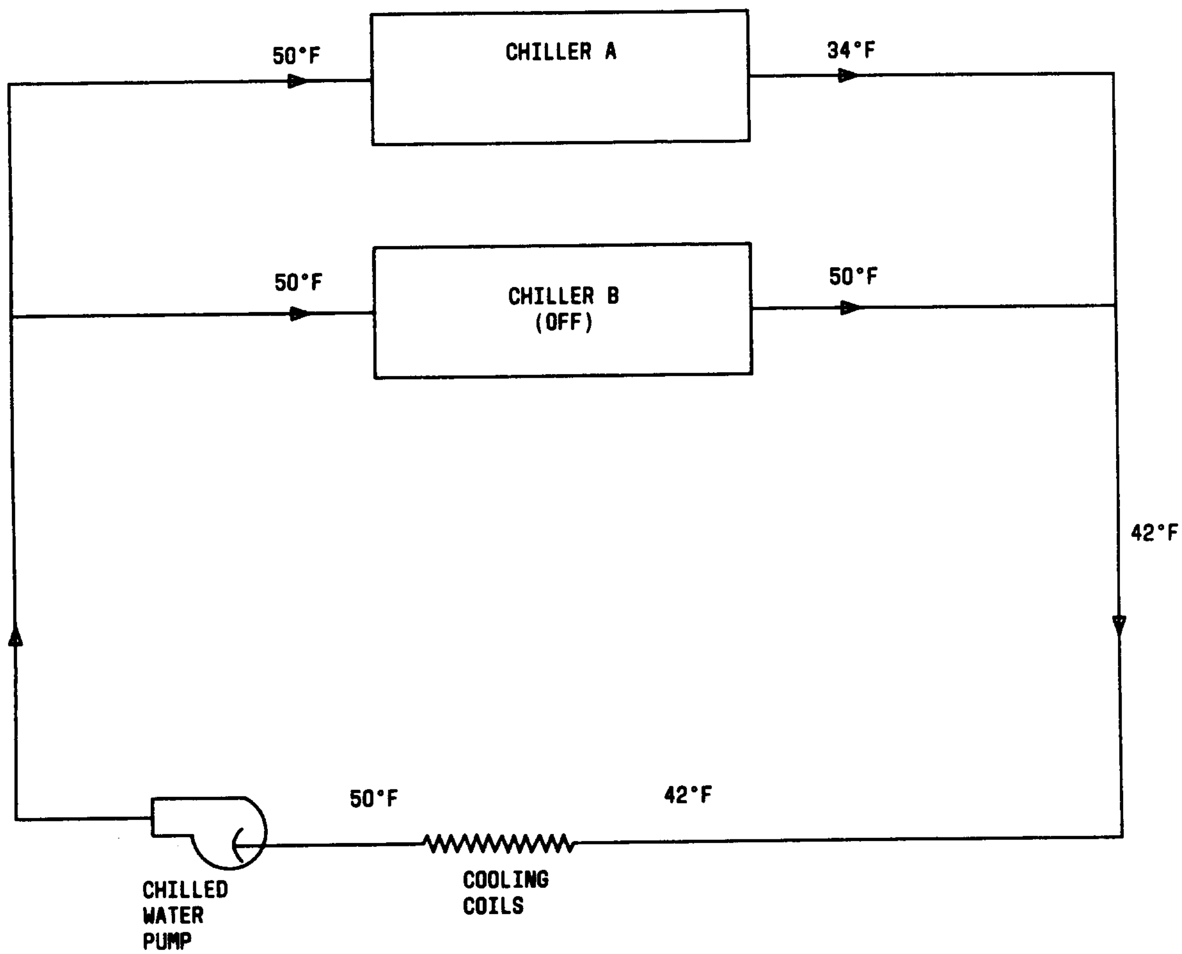

Fig. 3—One-Half Load in a Parallel Pipe Chiller System

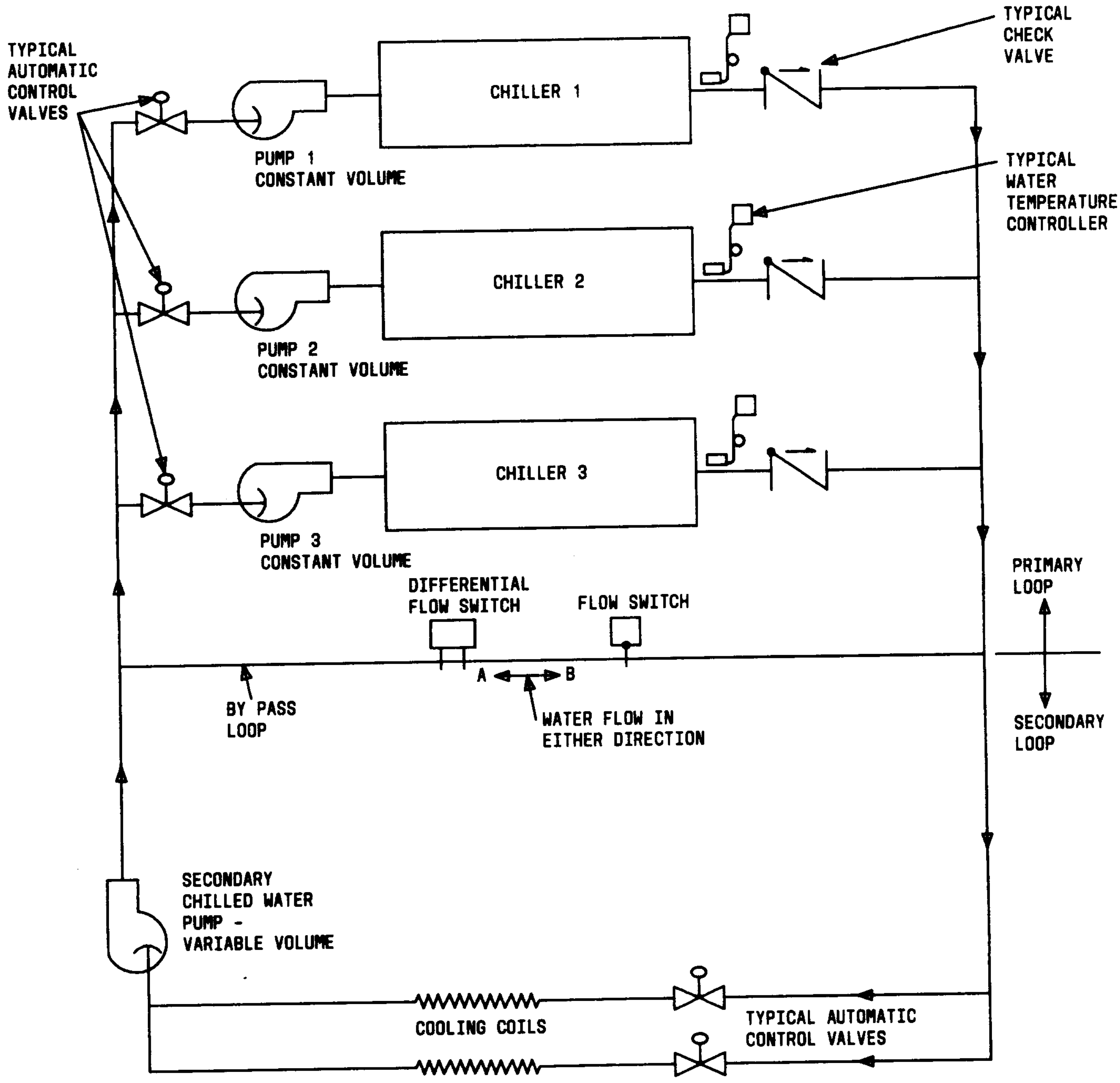

Fig. 4—Variable Water Volume Chiller System