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MINIMIZATION OF TRANSPORT AND DISTRIBUTION COST FOR DISTRICT HEATING STUDY OF PARTICULAR CASES

A. BARREAU (Faculté des Sciences d'Angers)
R. CAIZERGUES (CEA)
J. MORET BAILLY (IUT du Mans)

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STUDY OF SPECIAL CASES

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A. BARREAU (I.U.T DU MANS), R. CAIZERGUES (CEA), J. MORET BAILLY (I.U.T DU MANS)

1 - TRANSPORT AND DISTRIBUTION OF THERMAL ENERGY

The transport and distribution of hot pressurized water involve different sets of criteria and hence must be dealt separately.

1.1 - Transport networks

Transport networks are carrying hot water from heat source (Pool-type or PWR nuclear reactors, or fossil fuel plants) to towns or large industrial complexes which can use energy in this form.

They have, in general, few branches and large rates of flow. Towns and large industrial complexes are located at either junctions or terminations of the power transport networks.

Large diameter pipes (> 350 mm), some 5 or 20 or 30 kilometers long are employed.

A heat exchanger and a pump are used to couple transport and distribution networks : figure 1.

We are supposing for calculations that each pipe of transport network is independent with a pump.

1.2 - Heat distribution networks

Distribution networks have a great number of branches. Pipes have smaller diameters (< 250 mm).

A single pump is carrying hot water.

1.3 - Storages

Storages are very important. One or more hot water storage systems can be used in conjunction with the transport network. Suche system store hot water in summer and redistribute it in winter, when needed.

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It is possible to use others hot water storage systems in conjunction with distribution networks : such systems store hot water during the night and redistribute it when needed.

2 - MINIMIZATION OF TRANSPORT COST

2.1 - Method's description

Transport network optimization consists of two parts :

a) Calculation of every pipe's rates of flow in taking into consideration :
- Energy requierements (as defined by their monotonic power/times curves) and flow temperature's diminution : ΔT to junctions and terminations of transport network ;
- Storage's presence ;
- Variable cost of electric energy with season and time of day ;
- Cost of source's thermal energy ;
- Local fossil fuel plants.

A computer programme has been written to calculate rate of flow in each pipe.

b) Pipe diameter's calculation for each branch.

It is a simple calculation for transport network : each pipe's diameter is calculated independently.

2.2 - Operating costs

a) Discounted annual repayment cost for pipes : C_t

List of pipe's price C_t versus diameter : D is given. Price's function is calculated by programme :

$C_T = C_{TO} + A.D^B$ (Least square method)

$$C_t = \sum_{J=1}^{J=N} \frac{a \cdot C_t}{(1 + I)^N}$$

with :

$$a = \frac{I.(1 + I)^N}{(1 + I)^N - 1} \quad \text{: annual capital charge rate}$$

I is discount rate

N is number of repayment years.

b) Discounting annual cost of electrical energy supplied to the pump and repayment cost for pumps : C_p

1 - Electrical energy calculation

Rates of flow Q are calculated for each pipe and for each point of monotonic power/time curves. Flow's speed V is given by :

$$V = \frac{Q}{\rho \cdot \frac{\pi D^2}{4}}$$

ρ is fluid's density
Pressure drop = ΔP is calculated as : $\Delta P = \rho \cdot \Lambda \dfrac{V^2}{2D} \cdot L$

Friction factor L is given by COLEBRROK's formulation :

$$\frac{1}{\sqrt{\Lambda}} = -2 \, \ell g \left[\frac{2{,}51}{R_e \cdot \sqrt{\Lambda}} + \frac{\varepsilon / D}{3{,}72} \right]$$

ε characterizes pipe roughness.
R_e is REYNOLDS number.
Pu, pumping power is given by :

$$Pu = \frac{Q \cdot \Delta P}{\eta}$$

η : Pump efficiency

Monotone curve of figure 2 have five branches for five costs of electrical energy. Rate of flow/time curves have also five branches. For each pipe, $\dfrac{Pu}{Pu_{MAX}}$ is related to $\dfrac{Q}{Q_{MAX}}$ by :

$$\frac{Pu}{Pu_{MAX}} = \left(\frac{Q}{Q_{MAX}} \right)^{\alpha}$$

Pu_{MAX} and Q_{MAX} are maximum pumping power and maximum rate of flow:
$\alpha \neq 3$ if $R_e > 10^6$ and $\alpha \neq 2{,}75$ if $R_\varepsilon \geq 2.\ 10^5$

$$h_i = \int_{t_i}^{t_i+1} \frac{Pu \cdot dt}{Pu_{MAX}}$$

Electrical cost is equal to :

$$Pu_{MAX} \cdot \sum_{i=1}^{i=5} W_i \cdot h_i$$

W_i : electrical energy unit cost

2 - Constant cost of electrical energy
This cost is proportional to maximum pumping power.

Repayment cost for pumps
Pump's price is proportional to maximum pumping power and is equal to : $P_i Pu_{MAX}$: p_i is cost of power unit.
Repayment cost for pumps is :
$a_1 \cdot p \cdot Pu_{MAX}$
with : $a_1 = \dfrac{I \cdot (I + I)^{N_1}}{(I + I)^{N} - 1}$

N1 is number of repayment years for pump.

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Discounted annual cost of electrical energy supplied to the pumps and repayment cost for pumps is given by :

$$C_p = Pu_{MAX}\left(\sum_{i=1}^{i=5} W_i \cdot h_i + b + a_1 \cdot p\right)$$

$$C_p = \sum_{j=1}^{j=N} Pu_{MAX}(j)\left(\sum_{i=1}^{i=5} W_i(j) \cdot h_i(j) + b + a_1 p\right) \cdot \frac{1}{(1+I)^j}$$

j : is running number of year.

2.3 - Discounted annual cost for heat insulation system C_c

Cost for heat insulation is proportional to insulator volume

$$C_c = \Pi \sum_{j=1}^{j=N} ap_c \cdot E \cdot (D + E) \cdot L \cdot \frac{1}{(1+I)^j}$$

E is insulator thickness

p_c is cost of volume unit.

2.4 - Discounted annual cost for energy lost through pipe insulation C_L

Energy lost during time unit is given by :

$$\frac{2\Pi \cdot \lambda \cdot (T - Text)}{\ell n\left(1 + \frac{2E}{D}\right)}$$

1 is thermal conductibility. T is water temperature. Text is surrounding temperature.

Discounted annual cost for energy lost through pipe insulation : C_q is equal to :

$$C_q = \sum_{j=1}^{j=N} P_W \cdot 2\Pi \cdot \lambda \cdot \frac{(T - Text)}{\ell n\left(1 + \frac{2.E}{D}\right)} \cdot LL\ 8760 \cdot \frac{1}{(1+I)^j}$$

2.5 - Discounted network operating cost : C - Minimization of C

$$C = C_t + C_p + C_c + C_q$$

Pipe diameter D_m and thermal insulator thickness E_m which minimize C are given by system :

$$\frac{\partial C}{\partial D} = 0 \qquad \frac{\partial C}{\partial E} = 0 \text{ (for each network pipe)}$$

D_m value is between two real diameters values of price's list versus diameter D_i

$D_j \leqslant D_m \leqslant D_{j+1}$ (i = j, j+1)

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D_i value which gives the most little C value is chosen as pipe diameter value.

3 - DISTRIBUTION OF THERMAL ENERGY

The same parameters are introduced into this program as in transport calculations. The same method is used for rate of flow calculations. But, mathematical methods of pipe's diameter calculation are different.

Two methods of calculation have been used :

- LAGRANGE's method of undetermined multipliers
- BELLMANN theory (dynamic programming).

3.1 - LAGRANGE's method of undetermined multipliers

Distribution network has N branches and m terminations.

The difference between pressure pump Po and pressure drop between source and termination + pressure drop between termination and source ΔP_i equals 0.

$$P_o - \sum_{i=1}^{i=j} \Delta P_i = 0 = f_j \text{ (termination j)}$$

In LAGRANGE's method, function :

$$\psi = C + \sum_{j=1}^{j=m} a_j \cdot f_j \text{ is minimized}$$

αj (j= 1, m) are m undetermined multipliers. We have 2N + m equations

$$\frac{\partial\psi}{\partial D_i} = 0 \text{ (N)}, \quad \frac{\partial\psi}{\partial E_i} = 0 \text{ (N)}, \quad f_j = 0 \text{ (m)}$$

and 2N + m unknonws : D_i, E_i and α_j.

A computerized iterative method is used to solve system of N + m equations with n unknowns : programm Optal.

3.2 - Dynamic programming : ODYN program ODYN

A computerized version of BELLMANN's method enables real minimum costs to be calculated, pressure limitations, linear flow-rate limitations and real pipe diameters, being taken into account.

The parameters introduced are pratically the same as those of the analytical method.

It is possible to take the future growth of the network into consideration : creation of new branches, evolution of monotonic curves.

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Method's description : If network is "optimum", a part of network from a junctic is also "optimum" : minimum operating cost.

Pipe diameter calculation : to first step of calculation, x values of pressure drop ΔP_i are given for branches directly related to terminations (see figure 4 : branch j). Maximum ΔP_m is chosen. Values of ΔP_i are :

$$o, \frac{\Delta P_{MAX}}{x-1}, \frac{2\Delta P_{MAX}}{m-1}, \ldots\ldots, \Delta P_{MAX}$$

ΔP_i value is between ΔP_j, ΔP_{j+1} corresponding to two successive diameters D_j, D_{j+1} of pipe's price list : $\Delta P_j < \Delta P_i \; \Delta P_{j+1}$.

It is possible to calculate two pipe's lengths L_j, L_{j+1} corresponding to D_j, D_{j+1} diameters : branch j is made of two pipes : L_j, L_{j+1} lengths L_j and L_{j+1} are given by :

$$L_j + L_{j+1} = 2L$$

$$\Delta P_j \cdot L_j + \Delta P_{j+1} \cdot L_{j+1} = \Delta P_i \cdot 2 \cdot L.$$

Each branch has two pipes (lengths L_j, L_{j+1}; diameters D_j, D_{j+1})

Figure 3 shows branch j. Branches issued from junction N are known : x values of ΔP_i corresponding to x minimum values of C are determined.

Following junction M is related to N junction by branch j. x values of ΔP_k are given to N junction.

ΔP_k is pressure drop from junction N to termination + pressure drop from termination to junction N.

For each value ΔP_k, it is possible to associate x values ΔP_i and to calculate $\Delta P_{ki} = \Delta P_k - \Delta P_i$: pressure drop from M junction to N junction + pressure drop from N junction to M junction, pipe's diameter and length of branch j and operating cost C.

For each value of ΔP_k, we have x values of C and we choose minimum value of C.

For x values ΔP_k, we have x^2 values of C and we keep w minimum values of C.

Each ΔP_k, ΔP_i, D_j, L_j, D_{j+1} values corresponding to minimum C values are memorized.

When each branch directly related to M junction are studied (branch j and branch m), it is possible to study following junction L (branch ℓ).

Step calculation is ended when the last junction (source junction) is studied.

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We have x minimum values of network operating cost. The most little C and associated values : pressure drop to junctions, branches diameters and length are memorized.

Following steps : pressure range - ΔP_{MAX} is reduced around each ΔP_k associated to minimum C value (as shows figure 4). Calculations are begun again with new range of ΔP (x values) as far as pressure drop convergence to be ggod (15 steps).

4 - SOME EXAMPLES OF COST STUDIES

Some transport and distribution networks are studied with the corresponding computed programs :

- 52 branches network - 27 centimes (27 terminations)
- 287 branches network - 148 centimes (148 terminations).

4.1 - 52 branches network (figure 5)

Minimum operating cost has been calculated by analytical method : OPTAL program.

Program gives network characteristics : rates of flow, flow speeds, pipe's diameters, pressure drops C_t, C_p, C_c, C_g, C for each branch and for network (total costs). Total investment cost, pumping power, total pressure drop are also given.

In this example, maximum heat demand is 147 MW (127 kth/h). Hot water is produced by pool type nuclear reactor (90% of thermal energy) and fossil fuel plant (10% of thermal energy).

Hot water temperature to source way out is : 128°C. Return temperature is 55°C. Total pipes's length is : 17,4 km.

Maximum distance between source and terminations is ≠ 8 km. Heat transport cost is found equal to : 1,4 c/kWh (1,628 c/th).

Analytical method gives lowestoperating cost. But, it is not possible to account for speed limitations and pressure limitations in pipes. Intermediate pumping systems are necessary to reduce pressure in pipes.

4.2 - 287 branches network

287 branches network is studied for district heating of town of 200000 inhabitants.

Hot water temperature (source wayout) is 170°C. Hot water return temperature is equal to 80°C. Total pipe's length is : minimum distance between source and terminations is km.

Minimum operating cost has been calculated by dynamic programming method : ODYN program (a computerized version of BELLMANN's method.

Hot water is produced by pool type nuclear reactor : 100 MW power and fossil fuel plant.

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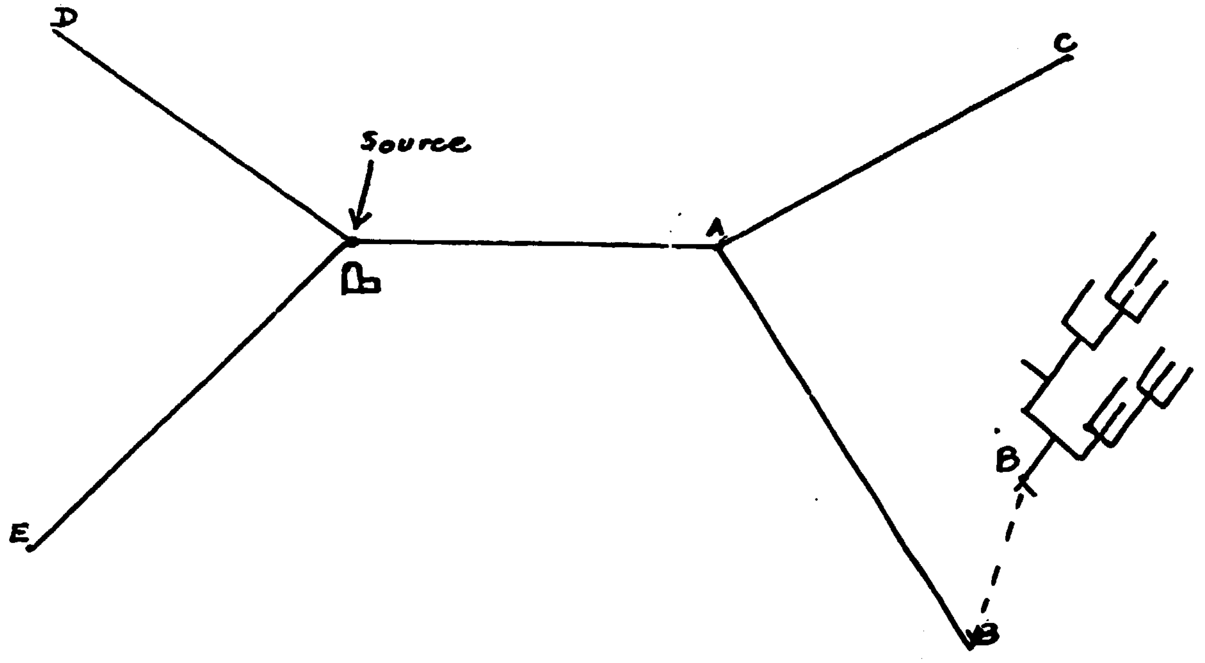
Maximum heat demabd is : 245 MW.

Nuclear reactor gives 80% of thermal energy. Complement of energy : 220% is given by fissil fuel plant when heat demand is greater than 100 MW.

ODYN program fives same outputs than OPTAL.

Transport cost of energy is found equal to 2,08 c/ kWh (speed limit 4,5 m/p).



(A, B, C, D, E are towns or large industrial complexes)

Figure 1

Hot water transport and distribution network - schema.

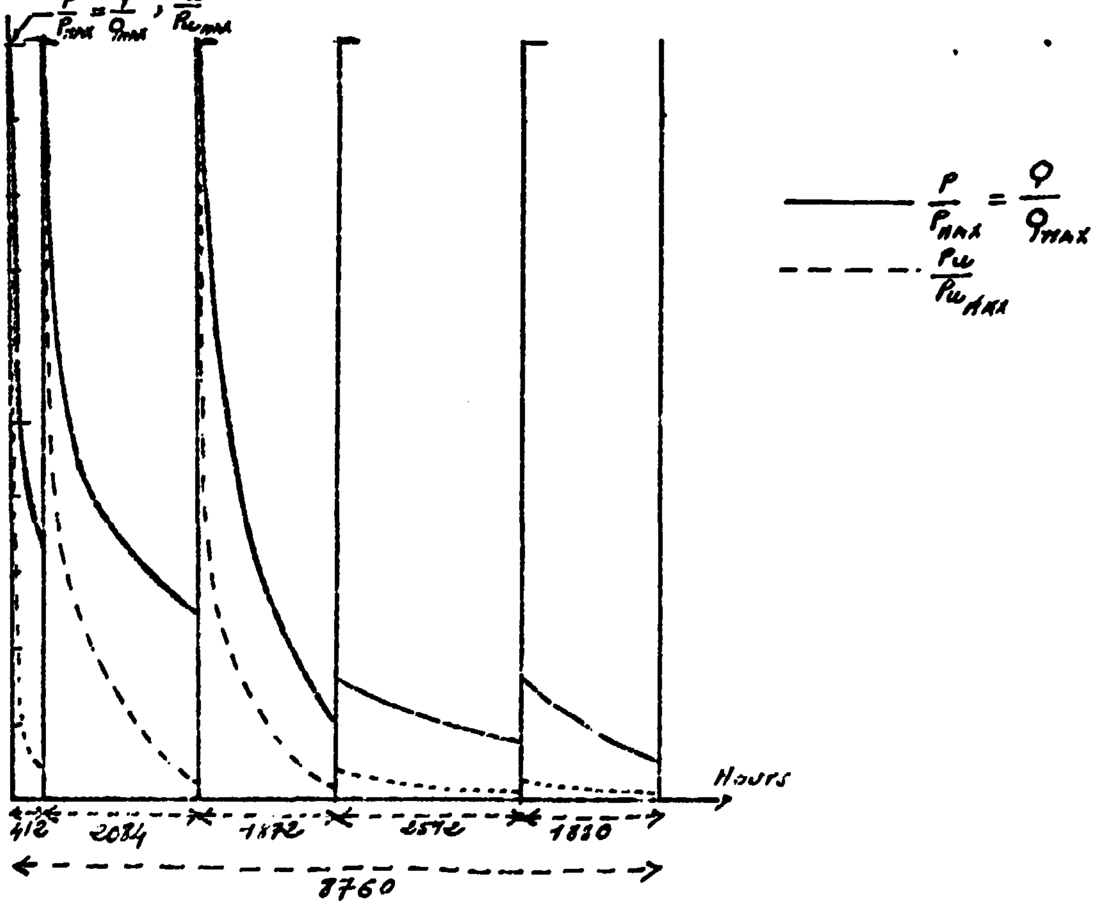


Figure 2

monotone curves $\frac{P}{P_M}$ vs Hours number, $\frac{Q}{Q_{MAX}} = \frac{P}{P_{MAX}}$ (ΔT = ct)

$$\frac{P_U}{P_{U_{MAX}}} = \left(\frac{Q}{Q_{MAX}}\right)^{\alpha}$$

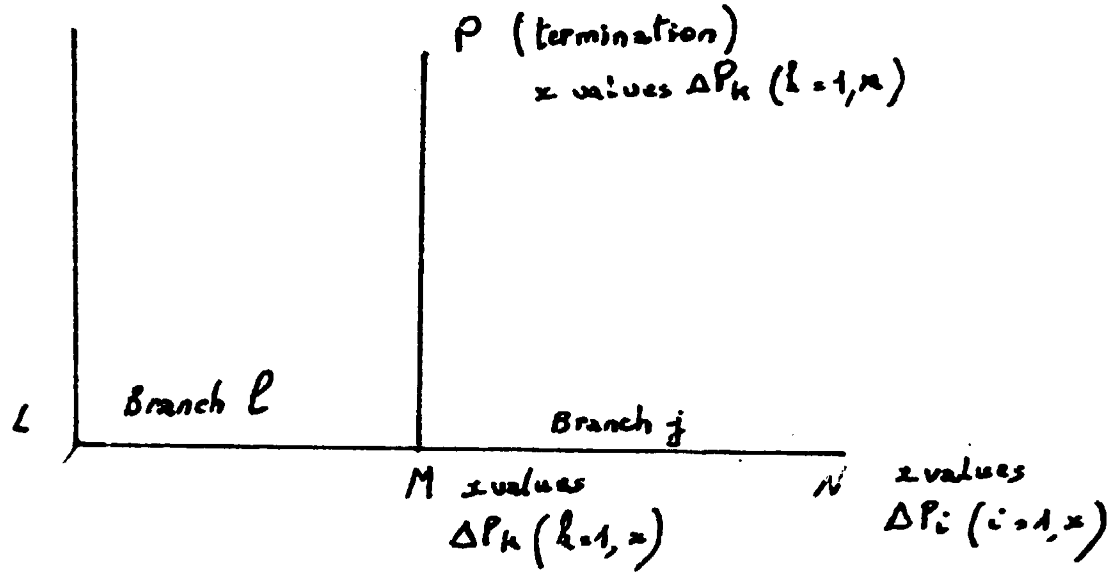


Figure n° 3

Dynamic programming

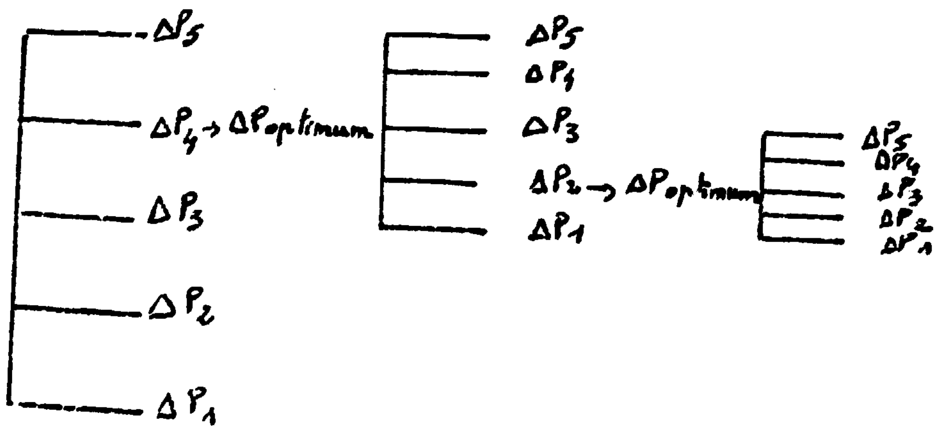


Figure n° 4

ΔP convergence to junction N

FIGURE 5

52 branches network