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

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STUDY OF SPECIAL CASES

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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. Such system stores hot water in summer and redistributes it in winter, when needed.

.../...
It is possible to use other 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 requirements (as defined by their monotonic power/time 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 pipes' price \( C_{1p} \) versus diameter: \( D \) is given. Price's function is calculated by programme:

\[
C_T = C_{T0} + A.D^B \quad \text{(Least square method)}
\]

\[
C_T = \frac{\sum_{j=1}^{J=N} a_j \cdot C_{1p}}{(1 + 1)^N}
\]

with:

\[
a = \frac{l. (1 + 1)^N}{(1 + 1)^N - 1} \quad \text{annual capital charge rate}
\]

\[l \quad \text{is discount rate}
\]

\[N \quad \text{is number of repayment years.}
\]

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

\[
T = \text{Electrical energy calculation}
\]

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:

\[
V = \frac{\pi D^2}{\rho} \quad \text{m/s}
\]
\( p \) is fluid's density

Pressure drop = \( \Delta P \) is calculated as: 

\[
\Delta P = p \cdot A \cdot \frac{V^2}{2D}
\]

Friction factor \( L \) is given by COLEBROOK's formulation:

\[
\frac{1}{\sqrt{L}} = -2 \log \left( \frac{2.51}{R_e \cdot \frac{V}{D}} + \frac{\varepsilon}{D} \right)
\]

\( \varepsilon \) characterizes pipe roughness.

\( R_e \) is REYNOLDS number.

\( \gamma \), pumping power is given by:

\[
\gamma = \frac{Q \cdot \Delta P}{\eta}
\]

\( \eta \) : 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, \( \gamma \) is related to \( Q \) by:

\[
\gamma \frac{\gamma_{\text{MAX}}}{\gamma_{\text{MAX}}} = \left( \frac{Q}{Q_{\text{MAX}}} \right)^{\alpha}
\]

\( \gamma_{\text{MAX}} \) and \( Q_{\text{MAX}} \) are maximum pumping power and maximum rate of flow.

\( \alpha = 3 \) if \( R_e > 10^6 \) and \( \alpha = 2.75 \) if \( R_e \approx 2 \times 10^5 \)

\[
h_i = \int_{i}^{i+1} \frac{\gamma}{\gamma_{\text{MAX}}} dt
\]

Electrical cost is equal to:

\[
\gamma_{\text{MAX}} \sum_{i=1}^{5} l_i \cdot \gamma_i
\]

\( l_i \) : Electrical energy unit cost

\( \gamma_{\text{MAX}} \) : 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: \( \gamma \cdot \gamma_{\text{MAX}} \cdot \rho \cdot \gamma_{\text{MAX}} \)

Repayment cost for pumps is:

\[
a_i = \frac{\gamma \cdot \gamma_{\text{MAX}} \cdot \rho \cdot \gamma_{\text{MAX}}}{(1 + 1)^N}
\]

with:

\[
a_i = \frac{\gamma \cdot \gamma_{\text{MAX}} \cdot \rho \cdot \gamma_{\text{MAX}}}{(1 + 1)^N}
\]

\( N \) is number of repayment years for pump.
Discounted annual cost of electrical energy supplied to the pumps and repayment cost for pumps is given by:

\[
C_p = \text{Pu}_{\text{MAX}} \left( \sum_{i=1}^{5} W_i \cdot h_i + b + a_1 \cdot p \right) + \sum_{j=1}^{N} \text{Pu}_{\text{MAX}}(j) \left( \sum_{i=1}^{5} W_i(j) \cdot h_i(j) + b + a_1 p \right) \cdot \frac{1}{(1 + 1)^j}
\]

\( j \) : 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

\[
C_c = \Pi \sum_{j=1}^{N} a p_c \cdot E \cdot (D + E) \cdot L \cdot \frac{1}{(1 + 1)^j}
\]

\( E \) is insulator thickness

\( p_c \) is cost of volume unit.

2.4 - Discounted annual cost for energy lost through pipe insulation \( C_q \)

Energy lost during time unit is given by:

\[
2 \pi \cdot \lambda \cdot \frac{(T - \text{Text})}{\ln (1 + \frac{2E}{D})}
\]

\( D \) 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:

\[
C_q = \sum_{j=1}^{N} \text{Pu}_{2\pi} \cdot \lambda \cdot \frac{(T - \text{Text}) \cdot \text{LL} \cdot 8760}{\ln (1 + \frac{2E}{D}) \cdot (1 + 1)^j}
\]

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:

\[
\frac{\partial C}{\partial D} = 0 \quad \frac{\partial C}{\partial E} = 0 \quad \text{for each network pipe}
\]

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

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

.../...
D. 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
- BELLMAN theory (dynamic programming).

3.1 - LAGRANGE's method of undetermined multipliers

Distribution network has \( N \) branches and \( m \) terminations.

The difference between pressure pump \( P_0 \) and pressure drop between source and termination + pressure drop between termination and source \( \Delta P_i \) equals \( 0 \).

\[
P_0 = \sum_{i=1}^{N} \Delta P_i = 0 = \sum_{j=1}^{m} \Delta P_j \quad (\text{termination } j)
\]

In LAGRANGE's method, function:

\[
\psi = C + \sum_{j=1}^{m} a_j \cdot \psi_j 
\]

is minimized

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

\[
\frac{\partial \psi}{\partial D_i} = 0 \quad (N), \quad \frac{\partial \psi}{\partial E_j} = 0 \quad (N), \quad \frac{\partial \psi}{\partial \alpha_j} = 0 \quad (m)
\]

and \( 2N + m \) unknowns: \( D_i, E_j \) and \( \alpha_j \).

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

3.2 - Dynamic programming: ODYN program ODYN

A computerized version of BELLMAN'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 practically 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.
Method's description: If network i is "optimum", a part of network from a junction is also "optimum": minimum operating cost.

Pipe diameter calculation: To first step of calculation, x values of pressure drop $\Delta P_i$ are given for branches directly related to terminations (see Figure 4: branch j). Maximum $\Delta P_{max}$ is chosen. Values of $\Delta P_i$ are:

$$\Delta P_i = \frac{\Delta P_{max}}{x-1}, \quad \frac{\Delta P_{max}}{m-1}, \ldots, \Delta P_{max}$$

$\Delta P_i$ value is between $\Delta P_i$, $\Delta P_{i+1}$ corresponding to two successive diameters $D_i$, $D_{i+1}$ of pipe's price list: $\Delta P_i < \Delta P_i, \Delta P_{i+1}$.

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

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

$$\Delta P_i \cdot L_i + \Delta P_{i+1} \cdot L_{i+1} = \Delta P_i \cdot 2 \cdot L.$$  

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 $\Delta P_i$ corresponding to x minimum values of C are determined.

Following junction M is related to N junction by branch j, x values of $\Delta P_k$ are given to N junction.

$\Delta P_k$ is pressure drop from junction N to termination + pressure drop from termination to junction N.

For each value $\Delta P_k$, it is possible to associate x values $\Delta P_i$ and to calculate $\Delta P_{k,i} = \Delta P_k - \Delta P_i$: 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 $\Delta P_k$, we have x values of C and we choose minimum value of C.

For x values $\Delta P_k$, we have $x^2$ values of C and we keep w minimum values of C.

Each $\Delta P_k$, $\Delta P_i$, $D_j$, $L_j$, $D_{j+1}$ 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.
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 - \( \Delta P_{\text{max}} \) is reduced around
each \( \Delta P_i \) associated to minimum C value (as shows figure 4). Calculations
are begun again with new range of \( \Delta P \) (x values) as far as pressure drop
convergence to be good (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 \( C_1, C_p, C_c, C_o, C \) 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 lowest operating 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 program-
ming 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.
Maximum heat demand is: 245 MW.

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

ODYN program gives same outputs than OPTAL.

Transport cost of energy is found equal to 2.03 c/kWh (speed limit 4.5 m/s).
(A, B, C, D, E are towns or large industrial complexes)

Figure 1

Hot water transport and distribution network scheme.

\[
\frac{p}{P_{\text{max}}} = \frac{Q}{Q_{\text{max}}}
\]

Figure 2

Monotonic curves \( p \) vs. hours number, \( \frac{Q}{Q_{\text{max}}} \) vs. \( \frac{p}{P_{\text{max}}} \) (\( \Delta T = \text{cf} \))

\[
\frac{P_{\text{max}}}{P_{\text{max}}} = \left( \frac{Q}{Q_{\text{max}}} \right)^n
\]
Snatch C

\[ P \text{ (termination)} \]
\[ x \text{ values } \Delta P_k (t \leq t_x) \]

\[ \text{Branch } \ell \quad \text{Branch } \delta \]

\[ M \quad \Delta P_k (t \leq t_x) \]
\[ \Delta P_i (t = t_x) \]

Figure n°3

Dynamic programming

\[ \Delta P_1 \]
\[ \Delta P_2 \rightarrow \Delta P_{\text{optimum}} \]
\[ \Delta P_3 \]
\[ \Delta P_4 \]

Figure n°4

\[ \Delta P \text{ convergence to junction } N \]