UN-INTERRUPTED DISTRICT HEATING SUPPLY IN THE EVENT OF AN ELECTRIC POWER FAILURE

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ABSTRACT
State-of-the-art district heating technology possesses a potential for being capable of continuing to supply building heating in the event of an electric power failure of long duration, a potential that has hitherto largely been overlooked or ignored.

In the case of direct connection of hydronic building radiator space heating systems to district heating networks, water circulation within the building can rather easily be maintained, as long as there is a circulation within the district heating network. But with indirect connection, providing hydraulic separation by means of a heat exchanger, the situation becomes more difficult, since circulation within the building will often depend upon an individual circulation pump driven by an electric motor.

Nevertheless, as is demonstrated in the paper, in many cases a substantial natural circulation effect of the classical type, depending upon a water density differential, can be established.

A further approach presented is a novel type of device comprising a small water turbine arranged to be driven by the district heating pressure differential across a substation. The turbine can deliver, by direct shaft connection or otherwise, enough energy to run the circulation pump. The two approaches can even be combined, such that probably a large share of all customers connected to a district heating grid could be supplied with full or almost full heating capacity, even at harsh weather conditions.

OCCURRENCE OF ELECTRIC POWER FAILURES
Failures in the electric power supply are quite common in developing countries and in newly industrialised countries, where they often occur even daily. Although outages are less frequent in industrialised countries, they do occur, sometimes in the form of big black-outs, and since so many central functions in our modern society are dependent on a continuous supply of electricity, power failures are a serious issue here as well.

There is a tendency that both minor and more serious outages currently are becoming more frequent. The reason for this probably lies in the fact that most electricity markets have become more liberalised, which has caused power companies to invest less in reserve generation capacity. Additionally, responsibilities for allocation of generating capacity and for reliable operation of regional power transmission have become less clear.

Electric power systems are obvious targets in warfare or in terrorist actions aiming at causing as much destruction and disturbance as possible. Therefore, wherever vital functions in our modern society depend on electric power supply, efforts should be made in advance to abate possible consequences of electric power failures.

Buildings whose heat supply will often fail in the event of an electric outage, provides an example in this respect. At first sight heating may not appear to be one of those functions that deserve particular attention in an analysis of emergency situations. However, if heat supply to buildings fails for many days during a winter season, consequences could be serious. What at first may appear as a loss of comfort would gradually evolve into a situation that could be life-threatening especially, of course, to weak persons. Also, if temperatures within buildings will go below 0ºC, freezing damages can be expected to occur within HVAC-systems.

It can be argued that the advance of the most centralised form of building heating represented by district heating, sometimes serving a majority of all buildings within a large city, has made building heating more vulnerable in certain respects. On the other hand, as this paper tries to demonstrate, district heating possesses a potential for upholding heat supply that has been largely overlooked or ignored.

DIRECT VERSUS INDIRECT CONNECTION OF SPACE HEATING SYSTEMS
When considering the possibility of upholding heat supply to buildings in the event of an outage on the public electricity grid, a distinction must be made between indirect and direct connection of hydronic space heating systems, i.e. if there is or is not a heat exchanger providing hydraulic separation within the substation.

Which one of these two principles should be adopted is an old discussion theme among district heating engineers representing various national practises. Direct connection, of course, is the simpler one, therefore cheaper to install, at least as long as one focuses on first costs for substations only. Another argument is that a heat exchanger unavoidably introduces a temperature differential to drive heat transfer from the primary to the secondary.
side, which constitutes a loss from a thermodynamic point of view.

Advocates of the indirect connection principle on the other hand argue that it allows for higher pressure levels in the district heating grid which is particularly convenient when the topography within the serviced area is characterised by significant height variations. Furthermore, there are advantages in terms of better control of water chemistry which makes corrosion problems easier to handle.

With direct connection in its simplest form, water circulation within a house will automatically be upheld, as long as circulation within the district heating network is maintained.

However, direct connections are usually not as simple as that, since at the entrance to a district heated house the connection scheme often comprises re-circulation of return water from radiators. Thus, when district heating grids are designed for high supply temperatures (often a maximum of 130°C or even higher in Germany, for instance), a lowering of temperature is required to avoid burning accidents (children touching radiators). Even when grids are designed for rather low temperatures (as in Denmark, where a maximum of 80°C is not uncommon), a three-way valve is often employed, to provide admixing in a proportion that is controlled according to an input value from an outdoor air temperature sensor; re-circulation is provided for by a pump installed in series with a non-return valve in the re-circulation line, fig. 1.

Fig. 1 Direct connection of hydronic space heating system to the district heating grid

In the latter case the control of the three-way valve can be designed such that in the event of an electric fall-out the spindle position will automatically turn such that there is no admixing at all. Admittedly, in-door air temperature will accordingly be less perfect, but it will not change dramatically, provided radiators are fitted with thermostatic valves.

BUILDING HEATING WHEN ELECTRICITY SUPPLY FAILS IN CASE OF INDIRECT CONNECTION

In order to tackle the situation which arises for indirectly connected buildings in the event of a power failure, we have addressed the following two issues:

Issue 1: How big an amount of heat supply can be maintained if the circulation pump of a hydronic radiator system within a building connected to a district heating grid stops, i.e. solely by virtue of the classical natural circulation effect caused by temperature-dependent water density?

Issue 2: Would it be possible to maintain circulation of radiator water by driving the circulation pump by a small water turbine in turn being driven by the district heating differential pressure prevailing across supply and return lines?

NATURAL CIRCULATION DRIVEN BY WATER TEMPERATURE DIFFERENTIAL

Back in time, radiator systems were usually designed to function without a circulation pump, i.e. by relying on the natural circulation effect that arises from decreasing water density at higher temperature. In modern building heating systems water circulation is instead normally provided for by a circulation pump. This is often combined with radiators being fitted with thermostatic valves whose reliable function depends on a certain pressure differential that can be attained by means of such a pump of a suitable size. Additionally, circulation pumps have made it possible to use more narrow distribution pipes within buildings which save installation costs.

In a co-operation with the district heating company (owned by E.ON Sweden) of the Swedish town Malmö the following question was posed: How big a fraction of the total district heating load could be maintained if electricity supply should fail? To this company, apart from the aforementioned concern about interrupted heat supply to customers, there is the additional incentive to answer this question that, for a number of heat production plants, viz. a CHP plant and industries supplying waste heat, it is essential that the district heating system can be relied upon as a heat sink.
Our research group first developed a theoretical simulation model of a typical radiator system, and then we performed field experiments within selected test buildings. Here, power supply to circulation pumps was cut off for a test period lasting some hours, and various temperatures within the buildings were monitored (ref. 1). The automatic heat control systems within the substations were of a standard type. That is, in normal function the outgoing temperature within the radiator system is adjusted automatically according to a control curve, acting on an input signal from an outdoor air sensor. The control apparatus is fed with electric power that was cut off along with interruption of power supply to the pump. This caused the spindle of the motor valve (arranged in series with the heat exchanger) to stop in the position it had prior to the interruption test. All-in-all, conditions were such as they can be expected to be in case of an un-intended power failure.

Results from these experiments have been surprisingly encouraging. Fig.2 shows a recording from one of the experiments. As can be seen, nearly all heat supply could be restored on a day with an outdoor air temperature of around 0°C. Indoor air temperatures (not shown in the diagram) sustained fairly evenly distributed among various rooms of the building.

![Fig. 2. Power failure test. Power supply to radiator circulation pump and control equipment was cut off shortly before 9.45 and was resumed shortly after 11.30 AM. As can be seen, after some time around 85% of the original heat supply was restored. (Upper diagram: blue lines correspond to primary (DH) side and red lines to secondary (radiator) side, solid lines are supply and dashed lines return temperatures. Middle diagram: outdoor temperature. Lower diagram: Relative radiator circulation flow (red) and relative heat output (turquoise)). (ref. 1)](image)

A main reason why a strong natural circulation effect took place was that the outgoing temperature to the radiators rose, as can be seen, increasing the density differential caused by differing water temperatures in risers and downcomers. The temperature rise was caused by the considerably reduced circulation flow (when the pump is shut off).

The experiment recorded here was made for a building with rather tough conditions in that the heating system is designed for pump circulation, i.e. pipes were of fairly small dimensions and the radiators were fitted with thermostatic valves that pose a significant increase in flow resistance. Also, the building (which was a school) mainly just had one storey. The natural circulation effect is enhanced in a higher system.

Experiments with other buildings resulted in various degrees of maintained heat supply. Fig. 3 shows a summary of all performed tests. Outdoor temperatures varied from 0-10°C.
The 11th International Symposium on District Heating and Cooling, August 31 to September 2, 2008, Reykjavik, ICELAND

Fig. 3 Summary of performed power failure tests.

TURBINE-DRIVEN CIRCULATION PUMP

The concept with a small turbine described under ‘Issue 2’ here above we have coined: ‘Autonomous District Heating’. The idea was conceived 15 years ago independently by one of us (Frederiksen) and R. Johnsson (ref. 2), who at that time was in charge of district heating in Malmoe. Fig. 4 shows part (heating of domestic hot water not shown) of a substation scheme incorporating the proposed concept.

As can be seen, the radiator circuit is separated from the district heating grid by a heat exchanger, i.e. we assume what is commonly termed ‘indirect connection’. Those who favour direct connection, where radiator circuits inside building are effectively parts of the total district heating network circuit, may argue that this connection principle has an inherent facility of maintaining heat supply to buildings at a power failure. However, various types of connection schemes in fact do incorporate individual pumps in buildings as well.

The symbolic element in the figure representing connection of turbine and pump shafts could be devised in several alternative ways. It could be a simple, mechanical connection, perhaps incorporating a gearing. Another option would be to have the turbine driving a generator which in turn supplies electric energy to a pump motor. Some of the issues to be addressed when deciding upon these matters are:

- Optimal / suitable turbine and pump shaft speeds,
- Conversion losses associated with a possible generator and a possible motor,
- Robustness,
- Price

Fig. 4. Schematic of part of a district heating substation with a radiator system circulation pump driven by a water turbine arranged on the primary side of a heat exchanger. Domestic hot water provision is left out of the schematic for the sake of simplicity.
During the years that have lapsed since the idea of ‘Autonomous district heating’ was conceived, we have occasionally suggested the concept to industry, without striking much resonance. But two years ago a big storm occurred in Sweden which caused serious disturbance to electricity supply in large areas of the country. This prompted state authorities to implement a comprehensive review of the security of energy supply systems and led to a renewed interest in our concept. Göteborg Energy AB, represented by Mr. Gunnar Nilsson, chief engineer, accepted to give the idea a try in practice. The town of Göteborg (Gothenburg) counts around 500,000 residents. Field experiments to implement the concept are currently being planned.

A rough calculation example will illustrate the potential viability of the concept:

The aggregate efficiency of the turbine – pump device can be stated as

$$\eta_{aggr} = \frac{Q_{pump,s}}{Q_{pump,p}} = \frac{(V \cdot \Delta p)_s}{(V \cdot \Delta p)_p}.$$  

Using the energy balance for the transferred heat in the substation

$$Q = (\rho \cdot V \cdot c_p \cdot \Delta T)_p = (\rho \cdot V \cdot c_p \cdot \Delta T)_s$$

and simplifying it to

$$\frac{V_s}{V_p} = \frac{\Delta T_p}{\Delta T_s},$$

one ends up with

$$\eta_{aggr} = \frac{\Delta p_s}{\Delta p_p} \cdot \frac{\Delta T_p}{\Delta T_s}.$$

Let us assume that in a certain load condition the incoming and outgoing district heating temperatures are 105 and 45°C, respectively, and that temperature rise in the radiator system is from 40 to 70°C. Further, assume that the pressure differential on the primary side of the substation is 5 bars, and the pressure rise produced by the circulation pump is 0.25 bars. Neglecting various pressure losses (such as in the heat exchanger), this will require the aggregate efficiency of the turbine – pump device to be only:

$$\eta_{aggr} = \left( \frac{0.25}{5} \right) \left( \frac{105 - 45}{70 - 40} \right) = 10\%$$

In an arrangement with no other losses than those associated with the turbine and the pump, such a performance could be provided by, for instance, a turbine efficiency of 25% and a pump efficiency of 40%. These figures give a hint that – at least with buildings that are not too small – the concept could work. For a medium-sized building the size of the turbine would be in the order of 1 kW. Such a small turbine is not common in the market, so the size of the turbine would be in the order of 1 kW.

Recently, in a co-operation with Danish pump manufacturer a prototype of a turbine-driven pump has been made. So far, in laboratory tests it has performed according to expectations. This prototype is now being installed in a substation of the Gothenburg district heating network in order to make field tests.

**PUMPS AS TURBINES (PAT)**

A number of people have worked with a concept termed PAT, Pumps As Turbines (refs. 3 & 4). It turns out that small pumps can simply be run ‘in the reverse’ as turbines, with a reasonably high efficiency. The main application for such turbines has so far been in small hydroelectric installations to serve singular buildings located in the neighbourhood of a river or a creek and away from a reliable public grid.

One of the attractions with the PAT hydroelectricity concept, especially in less industrialised countries, is that small pumps can be bought off-the-shelf almost anywhere in the world. When there is a wish to improve the pump efficiency this can be achieved by rounding off blade edges in the exit section of the device running in the pump mode.

As an overall term, extremely small turbines with an output below 5 kWs, have been termed ‘pico turbines’. Examples of ‘pico hydropower’ can for instance be found in Indonesia (ref. 5) and in Kenya (ref. 6).

**RUNNING A TURBINE-PUMP DEVICE CONTINUOUSLY**

Over the years, pump manufacturers of have spent many efforts to improve the efficiency of their products, to contribute to save expensive electrical energy. It can be argued that our idea of having a pump driven by a turbine represents a dramatic, indirect leap forward in this development within the field of district heating applications, since we are utilising mechanical energy that is otherwise lost by throttling in control valves in series with heat exchangers.

From a district heating system point of view, savings will admittedly often amount to no more than a few % of the transmitted heat energy. Furthermore, it can be argued that a pressure drop due to throttling in an incompressible fluid results in an incremental water temperature rise, in accordance with the First Law of Thermodynamics, so in that sense energy is of course not lost. But usually, 1 kWh electric power is valued higher than...
1 kWh heat energy. Losses in pump motors add to building heating, which is beneficial in the heating season, but the opposite during summer.

Thus, the savings can be valued very differently, depending on the perspective.

**COMBINATION OF NATURAL CIRCULATION AND A TURBINE-DRIVEN PUMP**

How much could the turbine-driven pump concept be downsized – even down to applications in single-family dwellings? Naturally, since both pump and turbine efficiencies go down with smaller size, there may very well be some lower limit. In addition to pure technological considerations there is a question of economic viability; it would appear that the smaller the size, the less sophisticated a device, including control equipment, could be justified.

On the other hand, lost heat supply may be more serious to people living in single-family dwellings: The ratio of building envelope to volume in those buildings is relatively big, so cooling-off will take place more rapidly. They may have to leave their homes while people living in buildings with more apartments could gather within one apartment while still having easy access to their own apartment.

Since a turbine-driven device in most cases can be supported by the natural circulation effect, even a device with a very low efficiency could be justified.

Single-family dwellings with only one storey and without a cellar appear to be the most difficult case since here small size and weak natural circulation coincide. Here, direct connection instead of indirect connection with a heat exchanger between the primary and secondary circuits, can provide a simple solution to the problem, such that the entire stock of buildings connected to the district heating grid could uphold heat supply when electricity fails.

**FLOW DISTRIBUTION WITHIN A DISTRICT HEATING GRID**

If the ambition is to provide heat supply to all buildings in the event of an electric fall-out, careful attention must be given to pressure variation throughout the entire network. Fig. 5 here below shows a simplified schematic of pressure variation from a central pump to network periphery. As can be seen, the pressure differential between supply and return line is much bigger at the central pump, compared to the size of the differential towards the periphery of the service area.

At locations where a big pressure differential prevails, conditions for a turbine-driven pump to attain a high efficiency are much better than elsewhere. If turbine-pumps operating in substations far away from the main circulation pump shall be capable of functioning during an electric fall-out, it is essential that the control of substations operating at high pressure differentials is such that there will be rather tight limits to maximum individual, primary side flow-rates, such that substations close to main circulation pumps will not ‘steal’ excessive flow which would lead to unacceptably small pressure differentials farther away from the pump.

If pressure reserves are available in the network, pressure rises in network circulation pumps could be increased at an electric fall-out, either automatically or at the discretion of operating personnel. Thus, one could suspend the usual type of control whereby the speed of the central pump is maintained at a level that will keep the pressure differential at network periphery only slightly in excess of a minimum value of pressure differential (for instance 1 bar).

**ALTERNATIVE BACK-UP OPTIONS**

It is already common practice to provide various types of buildings with back-up equipment that can supply electric power in the event of a general electric black-out. Common examples are hospitals and buildings housing vital computer facilities. Often, but not always, such back-up will comprise all building equipment running on electric power, including circulation pumps.

Alternative back-up options can be divided into two categories: First, there is equipment that can run continuously, and secondly there is equipment that can only provide back-up for a limited time of operation. A typical example of the first category is an emergency diesel plant. Considering all equipment required in addition to the diesel itself and the necessity for regular check start-ups, this option can hardly be said to be a viable one for the great majority of buildings, in particular within inner city areas.

Battery back-up is an alternative that can run until its capacity has been emptied. Since it may be realistic to fit almost any building with a battery, this
is at present perhaps the most relevant alternative against which the turbine-driven alternative should be held up. However, there are both maintenance and capacity problems with this alternative. In a longer perspective, fuel cells represent an alternative that seems to deserve serious consideration. In comparison with many alternative back-up options the turbine-driven concept has the advantage that it can probably be designed as a very robust device that would require a minimum of overhaul and attention.

CONCLUSIONS AND OUTLOOK

Our investigations seem to encourage the idea of making district heating capable of serving connected buildings with heat energy in the event of a major power failure. As we have seen, such a facility can rely on natural circulation, on a turbine-driven circulation pump, or on a combination. Additionally, if the pump is driven continuously by the turbine, there will be a saving of electrical energy. The viability of the turbine-driven circulation pump concept has not been proven empirically yet, but work in that direction is in progress.

The prospect of a more or less un-impaired heat supply in the event of a power failure could be a good additional sales argument for district heating companies, especially where district heating competes with electrical resistance heating or with small heat pumps, two types of building heating that can hardly be made independent upon electric power supply.

Finally, it deserves mention that a district heating system additionally should easily be capable of providing heat for domestic hot water without interruption, on the premise that one can rely on supply of towns’ water. Since drinking water is vital for human survival this should be a matter of course. We are indeed aware that many water works have made provision for diesel back-up to their supply pumps, but if those who are responsible for district heating supply in a certain location are not sure, perhaps they should make a check upon this matter.

ACKNOWLEDGEMENTS

The work regarding natural circulation was funded by the Swedish Energy Agency, the municipalities of the city of Malmö, Stadsfastigheter (owner of municipal properties in Malmö), MKB Fastighet AB (owner of a large share of multi-dwelling buildings in Malmö), Swedish District Heating Agency and the energy company E.ON Värme Sverige AB.

Thanks are extended to Göteborg Energi AB, Sweden, for both co-operation and funding and to Grundfos A/S for co-operation regarding development of a turbine-pump prototype.

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