Int. J. Heat Mass Transfer. Vol. 15, pp. 433-442. Pergamon Press 1972. Printed in Great Britain

NON-STATIONARY OPERATION OF A STAGGERED PARALLEL SYSTEM OF BLAST FURNACE STOVES

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(*Received* 2 *April* 1971)

Abstract—A theoretical study is made of the optimal operation of staggered parallel blast furnace stoves under non-stationary conditions, caused by load changes. Two different types of load changes are considered. The first type consists of those changes that can be accommodated by the stove system at once. For this type of load changes the problem is studied how to return the system as quickly as possible to stationary operating conditions after step changes in the load. The second type of load changes consists of changes that are too large to be accommodated at once. Here a two-stage operation is envisaged: In the first stage the heat content of the stoves is built up to the point where the demanded load can be accommodated, and in the second stage the system is returned to stationary operating conditions. Numerical results are given for a particular stove system.

NOMENCLATURE

i, integer, indicating the period number following a load change;
n, integer, indicating the number of periods in phase 1 of a large load change;
$P[i]$, duration of the ith period [min];
P_{sta}, stationary period duration [min];
S, reversal time [min];
$T_0[i]$, hot blast temperature delivered during the ith period [°C];
T_{od}, desired hot blast temperature [°C];
V_g, gas flow rate during the heating phase [m^3/s, NTP];
$V_{g\,max}$, maximal gas flow rate during heating phase [m^3/s, NTP];
$V_{g1}[i]$, gas flow rate during the ith period of the stove that is in the first part of the heating phase [m^3/s, NTP];
$V_{g2}[i]$, gas flow rate during the ith period of the stove that is in the second part of the heating phase [m^3/s, NTP];
$V_0[i]$, hot blast flow rate delivered during the ith period [m^3/s, NTP];
V_{od}, desired hot blast flow rate [m^3/s, NTP];
λ, a constant.

INTRODUCTION

STAGGERED parallel operation of blast furnace stoves has been introduced relatively recently [1–4]. In this mode of operation four stoves are used. At any given instant of time two of the stoves are being heated up, while the other two simultaneously supply the blast. The outgoing flows of the two stoves in the cooling period are mixed to obtain the required flow of the desired temperature. We shall refer to the combination of required blast flow and desired blast temperature as the *load* of the stove system. Figure 1 gives a schematic representation of the stove arrangement. Figure 2 indicates the principles of staggered parallel operation.

In an earlier paper [5] the optimal stationary operation, i.e. operation with constant load, of a staggered parallel system has been investigated. The present paper is devoted to an analysis of

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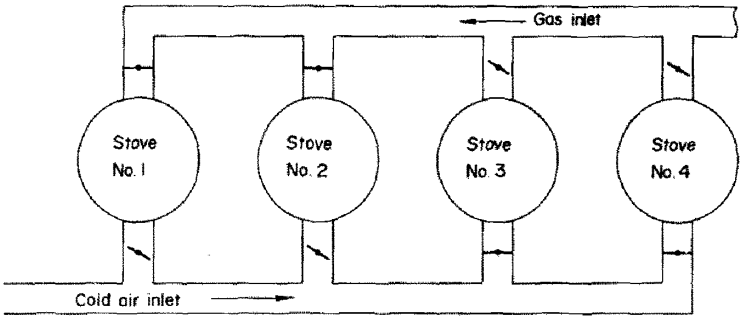


FIG. 1. Schematic representation of the stove arrangement.

non-stationary operation, i.e. operation under load changes. Computations will be given that show how after a load change the stove system may be guided to a new stationary mode of operation such that

(1) the duration of the upset caused by the load change is minimized;
(2) if the load change cannot be accommodated immediately, the period during which the system falls short of the demand is minimized.

We shall distinguish between two types of load changes, referred to as "small" changes and "large" changes. Small load changes are changes that can be accommodated by the stove system at once, i.e. immediately following a change in demand the two outgoing hot blast flows can be adjusted so that the new demand is met, and this condition can be maintained permanently. Large load changes are changes where it is either impossible to adjust the flows so as to meet the demand, or the system cannot sustain the load and "collapses", i.e. the cycle period decreases until the demanded load can no longer be supplied. Load *decreases* always are small load changes.

SYSTEM DESCRIPTION AND SIMULATION

It will be assumed in this paper that the staggered parallel system of stoves is operated according to the following principles:

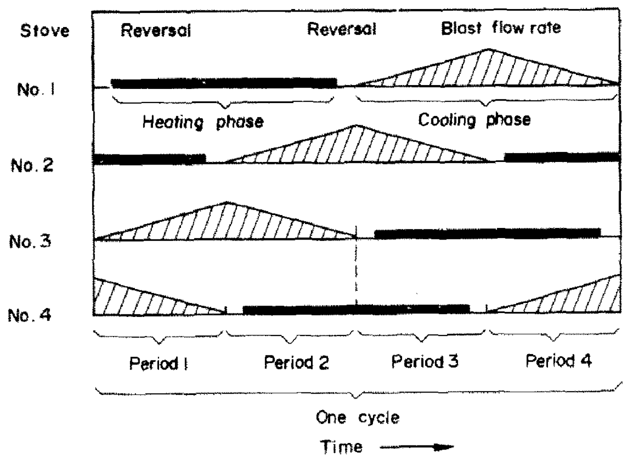


FIG. 2. Schematic representation of staggered parallel operation.

1. During the entire heating phase of a stove the flow rate V_g of the hot gas is kept constant. The magnitude of the flow rate is to be suitably selected for each period. It is not to exceed a given value $V_{g\ max}$
2. During the heating phase of a stove the fuel-to-air-ratio in the combustion chamber is so chosen that the gas inlet temperature at the top of the chequer work attains its maximally permissible value.
3. The total reversal time S, needed to change a stove over from the heating phase to the cooling phase and vice-versa, is taken from the heating period.
4. At each instant of time the two outgoing hot blast flows are so adjusted that (i) the total demanded hot blast flow rate is supplied, and (ii) the demanded hot blast temperature is delivered.
5. A new period is initiated (i.e. the stove in the cooling phase that has longest been in the cooling phase is changed over to the heating phase and the stove that has longest been in the heating phase is changed over to the cooling phase) as soon as the outgoing hot blast flows can no longer be adjusted so that the demanded hot blast temperature is delivered.
6. Load changes are only made at the beginning of a new period.

Furthermore, the following assumptions are made:

(a) All four stoves are physically identical.
(b) After a load change the load remains constant sufficiently long to allow the system to return to stationary conditions.

For the investigations to be described in this paper it has been necessary to develop a digital computer programme to simulate the stove system behaviour over a number of periods. This computer programme has been written using the usual partial differential equations that describe the heat transfer process in the chequerwork (see e.g. Wilmott [6]). The numerical approach described in an earlier paper [5], which is essentially identical to the method of Wilmott [6], has been adapted for the non-stationary case.

For what follows, it is important to understand the function of this simulation programme. For given initial chequerwork temperature profiles for each of the stoves, a given sequence of loads and a given sequence of fuel gas flow rates the programme simulates the behaviour of the stove system. We shall be particularly interested in the durations of the successive periods (in our terminology a *period* is the time interval that elapses between two successive change-overs of the system).

The four initial chequerwork temperature profiles are assumed to be given. Let $P[i]$, $i = 1, 2, \ldots$, denote the duration of the ith period following a load change. Similarly, $T_0[i]$ denotes the blast temperature delivered during the ith period, and $V_0[i]$ the blast flow rate delivered during the ith period. Finally, $V_{g1}[i]$ indicates the gas flow rate (i.e. the flow rate of the hot combustion gases that enter the chequerwork) during the ith period of the stove that is in the first part of the heating phase (i.e. during the preceding period this stove was in the cooling phase), and $V_{g2}[i]$ is the gas flow rate during the ith period of the stove that is in the second part of the heating phase (i.e. during the preceding period the stove was also in the heating phase).

The input to the stove simulation programme thus consists of the initial temperature profiles, the sequence of delivered blast temperatures $T_0[i]$, $i = 1, 2, \ldots$, the sequence of delivered blast flow rates $V_0[i]$, $i = 1, 2, \ldots$, and the sequence of gas flow rates $V_{g1}[i]$ and $V_{g2}[i]$, $i = 1, 2, \ldots$. The most important *dependent* variable that will figure in the following is the period duration $P[i]$, $i = 1, 2, \ldots$. Obviously, $P[i]$ is a function of $T_0[j]$ and $V_0[j]$, $j = 1, 2, \ldots, i$. Also, $P[i]$ is a function of $V_{g1}[j]$ and $V_{g2}[j]$, $j = 1, 2, \ldots, i-1$. From the latter variables we may omit $V_{g1}[i-1]$, however, since this quantity will not affect $P[i]$. The number of independent variables is further reduced by the fact that by assumption 1 at the beginning of this section the gas flow rate is kept constant during the entire heating phase so that $V_{g2}[j+1] = V_{g1}[j]$ for $j = 1, 2, \ldots$. As a result, we can say that $P[i]$ is a function of $V_{g2}[j]$, $j = 1, 2, \ldots, i-1$.

Now the main role of the stove simulation programme is to successively evaluate $P[i]$, $i = 1, 2, \ldots$, for given values of $T_0[j]$ and $V_0[j]$, $j = 1, 2, \ldots, i$ and $V_{g2}[j]$, $j = 1, 2, \ldots, i-1$. In the sequel it will be seen why these evaluations are needed. In practice it turns out that the dependencies of $P[i]$ on the independent variables is only mildly nonlinear, which is of great help in the numerical computations that are to be performed.

SMALL LOAD CHANGES

A small load change has been defined as a load change that can be accommodated by the stove system at once and permanently. The problem that has to be considered is how the stove system is returned to steady-stationary operating conditions after a load change. It is assumed that before the load change the system is in stationary operating conditions, and that after a change the load remains constant sufficiently long to allow the system to return to stationary conditions.

Now, *internally* stationary operating conditions are characterized by purely periodic operation, i.e. after a complete cycle has elapsed (consisting of four periods) the four chequerwork temperature profiles are identical to the initial profiles. *Externally* stationary operation is characterized by (i) equal and constant gas flow rates for each of the stoves in the heating phase, and (ii) constant durations of the periods. In earlier work [5] it has been found that the duration of the period during stationary operation determines to within very narrow limits the complete system cycle. During the same work it was found that there always exists a period duration for which the stationary operation has maximal thermal efficiency. The thermal efficiency is not very sensitive to changes in the period duration, however, and the optimal period duration does not vary much with the load.

In order to return the system as quickly as possible to stationary operating conditions after a load change we shall take the following approach. After the load change the blast temperatures $T_0[i]$ and the blast flow rates $V_0[i]$, $i = 1, 2, \ldots$, are set equal to the desired blast temperature T_{od} and the desired blast flow rate V_{od}, respectively. By suitably choosing the gas flow rates $V_{g2}[i]$, $i = 1, 2, \ldots$, the durations $P[i]$, $i = 1, 2, \ldots$, of the periods following a load change may be made as close as possible to the desired stationary period duration P_{sta} corresponding to the new load. This forces the system to operate with the stationary period duration, which in turn makes the system quickly settle in stationary operating conditions.

In order to force the period durations to be as close as possible to the desired period duration we proceed as follows: The first period duration, $P[1]$, cannot be influenced by adjusting the gas flow rates. $P[2]$ is solely determined by $V_{g2}[1]$, which we shall express as

$$P[2] = f_2(V_{g2}[1]). \tag{1}$$

Setting

$$P[2] = P_{sta}, \tag{2}$$

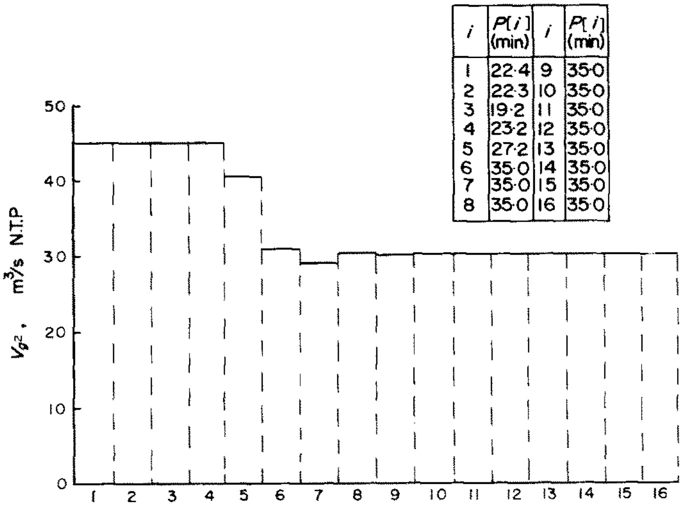
where P_{sta} is the desired stationary period duration, provides us with a single equation in the single unknown $V_{g2}[1]$, which numerically can easily be solved using a Newton–Raphson technique. When the solution of this equation does not satisfy the constraint

$$V_{g2} \leqslant V_{g\,max}, \tag{3}$$

the value of $V_{g2}[1]$ is set equal to $V_{g\,max}$. It can be checked beforehand whether the solution of (2) will satisfy (3) by computing $f_2[V_{g\,max}]$. If

$$f_2[V_{g\,max}] \leqslant P_{sta} \tag{4}$$

the flow rate $V_{g2}[1]$ must be set equal to $V_{g\,max}$.



i	$P[i]$ (min)	i	$P[i]$ (min)
1	22·4	9	35·0
2	22·3	10	35·0
3	19·2	11	35·0
4	23·2	12	35·0
5	27·2	13	35·0
6	35·0	14	35·0
7	35·0	15	35·0
8	35·0	16	35·0

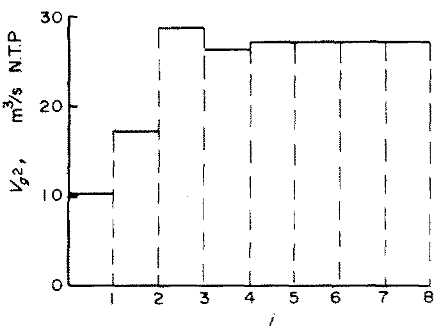
FIG. 3. The gas flow rate $V_{g2}[i]$ as a function of i after a temperature change of $+24°C$ in the hot blast temperature.

Once $V_{g2}[1]$ has been decided upon, $V_{g2}[2]$ may be found by requiring that $P[3]$ equal the stationary period duration P_{sta}. Since $P[3]$ is determined by $V_{g2}[1]$ and $V_{g2}[2]$, i.e.

$$P[3] = f_3(V_{g2}[1], V_{g2}[2]), \qquad (5)$$

setting $P[3] = P_{sta}$ provides us with a single equation for the single unknown $V_{g2}[2]$. Before applying the Newton–Raphson method to this problem, however, it should be verified whether the solution will satisfy (3) by computing $f_2(V_{g2}[1], V_{g\max})$ and checking whether this is larger than P_{sta}. If it is not, $V_{g2}[2]$ should be set equal to $V_{g\max}$. Continuing in this manner all fuel flow rates $V_{g2}[i]$, $i = 1, 2, \ldots$, can be successively computed.

Numerical computations have been performed for the stoves in use with Blast Furnace No. 6 of the Koninklijke Nederlandse Hoogovens en Staalfabrieken N.V. in Ijmuiden. The Netherlands. The chequerwork of each of the stoves is 32 m high, has a mass of 1351000 kg and a heating surface area of 43400 m². The physical data used in simulating the system is given in the earlier paper [5]. In each case the stationary condition *before* a load change is



i	$P[i]$ (min)
1	50·4
2	35·0
3	35·0
4	35·0
5	35·0
6	35·0
7	35·0
8	35·0

FIG. 4. The gas flow rate $V_{g2}[i]$ as a function of i after a temperature change of $-30°C$ in the hot blast temperature.

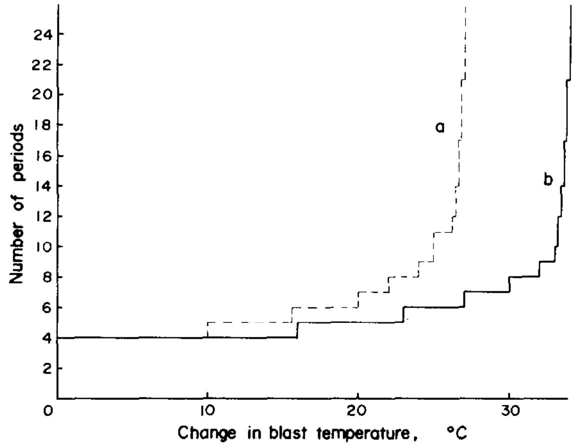


FIG. 5. The number of periods it takes the system to return to stationary operating conditions as a function of the change in the blast temperature:
(a) Initial blast temperature 1100°C;
(b) Initial blast temperature 1150°C.
The hot blast flow rate is always constant at 65 m^3/s (NTP), and the stationary period duration before and after the load change is always 35 min.

characterized by a hot blast flow rate of $V_0 = 65\ m^3/s$ (NTP), a hot blast temperature of $T_0 = 1150°C$ and a period duration of 35 min.

Figure 3 shows the gas flow rates $V_{g2}[i]$, $i = 1, 2, \ldots$, after a change of load consisting of a step of +24°C in the blast temperature. This change is near the maximal immediately attainable load change. The new desired period duration is 35 min. The successive period durations are tabulated in the figure. It is seen that the flow rate has to be kept at the maximal value $V_{g\ max} = 45\ m^3/s$ (NTP) during four

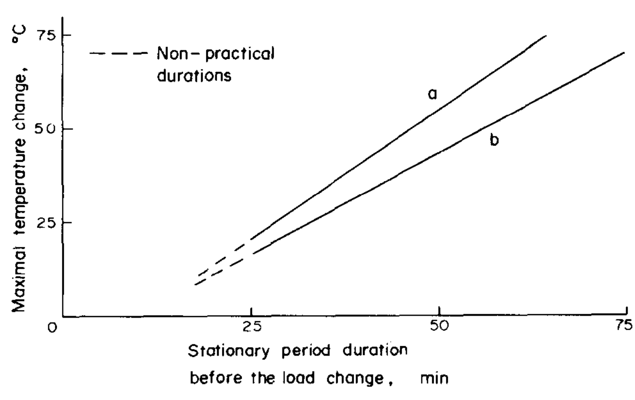


FIG. 6. The maximal temperature change as a function of the stationary period duration before the load change:
(a) Initial blast temperature 1100°C;
(b) Initial blast temperature 1150°C.
The hot blast flow rate is always constant at 65 m^3/s (NTP) and the stationary period duration after the load change is always 35 min.

periods. Following this another three periods are required to return to stationary operating conditions.

In Fig. 4 the gas flow rates are shown after a blast temperature change of −30°C. The new desired period duration is 35 min. This load change presents no problems. The gas flow rate is temporarily decreased, and it takes the system about four periods to return to stationary operation.

A question of some interest concerns the load change sizes that can be considered as small. This depends on the initial conditions. In particular it may be found that

(a) the maximally permissible small load change *decreases* when the load before the load change increases, and
(b) the maximally permissible small load change *increases* when the stationary period duration before the load change increases.

These facts are illustrated by the plots of Figs. 5–7. In Fig. 5 we give the number of periods it takes the system to return to stationary conditions as a function of the required hot blast temperature change. It is seen that for an initial blast temperature of 1100°C the maximal temperature change is +34°C, while for an initial blast temperature of 1150°C this change decreases to +27°C. Figure 6 gives the dependency of the maximal temperature change as a function of the period duration before the load change. Figure 7 provides some information about combined temperature and blast flow rate changes and shows the range of attainable small load changes for two initial conditions. Also this plot illustrates that the range increases when the load before the load change decreases.

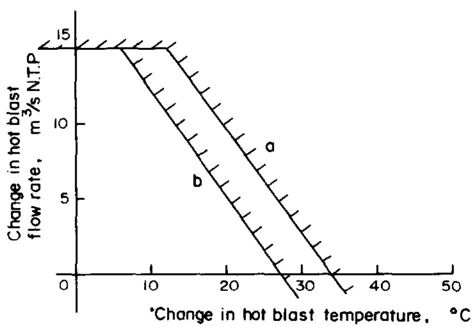


FIG. 7. The range of attainable small load changes:
(a) Initial blast temperature 1100°C;
(b) Initial blast temperature 1150°C.
The initial hot blast flow rate is always 65 m^3/s (NTP) and the stationary period duration before and after the load change is always 35 min. The horizontal boundary at the top is caused by the fact that the maximal blast flow rate is 80 m^3/s (NTP).

LARGE LOAD CHANGES

Large load changes are changes that cannot be accommodated at once or not permanently. They are detected in the course of the computations of the preceeding section when it turns out that sooner or later the stove system cannot deliver the required hot blast temperature, even if maximal gas flow rates are provided. Such a collapse of the system is accompanied by a steady decrease of the period duration after the load change.

In the case of a large load change we have to lower our aims and drop the requirement that the new demanded load be delivered at once. It has to be conceded that during a few periods immediately after the load change less than the demanded load is delivered. Once the heat content of the stove system is sufficiently built up the demanded load can be met and the system can return to stationary operating conditions. Thus, a two-stage operation is envisaged:

Stage 1. During n periods after the load change (n is to be determined) less than the demanded load is delivered. Using the maximal gas flow rates the heat content of the system is built up.

Stage 2. The duration $P[n+1]$ of the $(n+1)$th period after the load change is required to equal the new required stationary period duration P_{sta}, to guarantee that the demanded load can be met. As from the $(n+1)$th period the demanded load is delivered and the system is allowed to return to stationary operating conditions, using the small load change approach.

Thus, during stage 1 (the first n periods after the load change) the gas flow rates are kept fixed at $V_{g\,\max}$. The manipulated variables during this stage are the loads delivered during each period. In the following we shall assume that the demanded blast flow rate is always delivered so that the manipulated variables reduce to the delivered hot blast temperatures $T_0[1]$, $T_0[2]$, ..., $T_0[n]$. The terminal conditions for stage 1 are

$$T_0[n+1] = T_{od}, \tag{6a}$$

$$P[n+1] = P_{sta}, \tag{6b}$$

where T_{od} is the demanded hot blast temperature.

The two terminal conditions (6) leave considerable freedom in the choice of the hot blast flow rates when $n > 2$. Therefore, in order to minimize the upset introduced by the failure of the stove system to meet the demand we require that the delivered blast temperature be so chosen that the terminal conditions (6) for stage 1 are met *and* the quantity

$$\sum_{i=1}^{n} (T_{od} - T_0[i])^2 \tag{7}$$

is minimized. The number represented by (7) is large when during stage 1 the delivered hot blast temperatures differ greatly from the demanded temperature, and is small when the deviations are small. The choice of the quadratic sum criterion (7) is rather arbitrary, except that it is known that numerical optimization methods generally react favorably to quadratic objective functions.

We thus have obtained a function optimization problem, which consists of choosing the variables $T_0[1]$, $T_0[2]$, ..., $T_0[n]$ such that (7) is minimized subject to the constraints (6). For a given sequence of blast temperatures the conditions (6) may be verified by means of the simulation programme. The constraint (6a) is easily incorporated by forcing $T_0[n+1]$ to be equal to T_{od} while simulating the $(n+1)$st period. The constraint (6b) is taken care of by incorporating it into the objective function (7) and minimizing the function

$$\sum_{i=1}^{n} (T_{od} - T_0[i])^2 + \lambda(P[n+1] - P_{sta})^2, \tag{8}$$

where λ is chosen sufficiently large. This minimization problem was numerically solved by using a library computer subroutine based upon the Fletcher–Powell method (IBM Scientific Subroutine Package, Subroutine FMFP). The penalty function approach presented no special difficulties.

The outcome of this optimization problem provides the operating plan for stage 1. In order to determine the most suitable value of n the computation of stage 1 is repeated for different values of n. To compute the operating plan for stage 2 we follow the small load change approach, always delivering the demanded load and adjusting the gas flow rates such that the period durations remain equal to the required P_{sta}.

Numerical computations have been performed for initial conditions corresponding to stationary operation with a blast flow rate of 65 m^3/s (NTP), a blast temperature of 1100°C and a period duration of 35 min. The blast flow rate is kept constant, and the new desired period duration is 35 min. Table 1 lists the square root of the criterion (7) for different blast temperature changes and different values of n. It can be seen that as n increases the value of the criterion generally keeps decreasing. Figure 8 shows the

Table 1. The square root (°C) of the criterion (7) for different demanded hot blast temperatures and different values of n. *Blank entries have not been computed*

	n					
T_{od}(°C)	1	2	3	4	5	6
1140	56·8	33·9	24·3			
1150	79·6	52·0	43·6	39·4	35·9	
1160			63·0	58·4		
1200				139·7	140·2	140·4

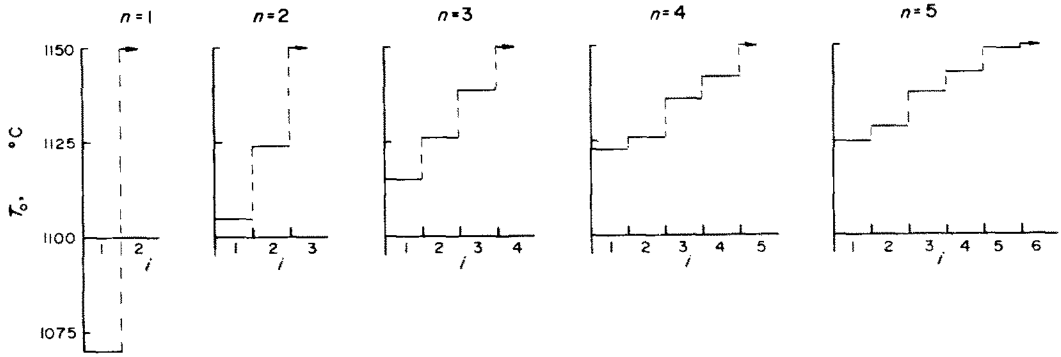


FIG. 8. Build-up of a large temperature change.

build-up of the hot blast temperature for a load increase of +50°C from 1100°C to 1150°C, for five different values of n.

It is difficult to decide which value of n is most suitable. For $n = 1$ the deviation from the required blast temperature is large but has a duration of one period only. For $n = 5$ the load is built up very smoothly and the deviations from the desired blast temperature are small but five periods are required. Which behaviour is more desirable depends on the operating requirements for the blast furnace itself, not on the stove system.

CONCLUSIONS

In this paper we have discussed how to operate staggered parallel blast furnace stove systems during load changes. It has been seen that after so-called small load changes the system requires about four to five periods to return to stationary operating conditions. After a large load change three to five periods are necessary to build up the new load, and following this another four to five periods are required to settle down to stationary operation.

A problem that also can be solved with the methods of this paper is the question how to operate the system when advance notification can be given of the time at which a load change is required and of the size of the load change. In such a case the heat content of the stove system can be built up before the change so that also large load changes can be accommodated at once.

It remains to discuss what the use is of the computations of this paper. This use is twofold:

(1) When the equations that describe the stove system behaviour are sufficiently accurate, the methods of this paper could be used in an on-line computer control system to predict the required gas flow rates in the case of a load change.
(2) In many instances it will not be possible or worthwhile to refine the system equations and fit them to the actual system operation to achieve the required accuracy of prediction. The qualitative results of studies as outlined in this paper, however, could be used to devise practical closed-loop control systems that make the stove system react to load changes roughly as computed in the present paper.

An interesting and fruitful topic of further study is an evaluation of present-day closed-loop stove control systems in view of the results of this paper, and the development of improved control systems.

ACKNOWLEDGEMENT

I would like to express my deep appreciation to Professor H. Kwakernaak, who introduced me into the field of system and control theory.

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OPÉRATION NON STATIONNAIRE DES RÉCUPÉRATEURS DE HAUT-FOURNEAU PARALLÈLES OSCILLANTS

Résumé—On fait l'étude théorique de l'opération optimale des récupérateurs parallèles oscillants de haut fourneau sous des conditions non stationnaires, causées par les changements de charge. Deux types différents de changements de charge sont considérés. Le premier type consiste en des changements qui peuvent être accommodés en une seule fois par le système récupérateur. Pour ce type de changement de charge, on étudie comment le système retourne aussi rapidement que possible à des conditions opératoires stationnaires après des changements échelons de charge. Le second type de changements de charge concerne ceux qui sont trop grands pour être accommodés en une seule fois. Ici on envisage une opération à deux étapes; dans le première étape la capacité calorifique des récupérateurs atteint le point où la charge demandée peut être accommodée, et dans la seconde étape le système retourne à des conditions opératoires stationnaires.

On donne des résultats numériques pour un système de récupérateur particulier.

INSTATIONÄRER BETRIEB EINES VERSETZTEN PARALLELSYSTEMS VON HOCHÖFEN

Zusammenfassung—In einer theoretischen Studie wird die optimale Betriebsweise von versetzten, parallel arbeitenden Hochöfen unter instationären Bedingungen untersucht, die durch Laständerungen hervorgerufen sind.

Es werden zwei verschiedene Arten von Laständerungen in Betracht gezogen. Die erste besteht in solchen Änderungen, denen sich das Ofensystem sofort anpassen kann. Für diesen Fall wird untersucht, wie man das System nach sprunghafter Laständerung schnellstmöglich zu stationärer Betriebsweise bringen kann.

Beim zweiten Typ sind die Laständerungen so gross, dass keine sofortige Anpassung möglich ist.

Hier wird eine Zweistufenoperation vorgesehen: Im ersten Abschnitt wird der Wärmeinhalt des Ofens so erhöht, dass die verlangte Last bewältigt werden kann, und im zweiten Abschnitt wird das System wieder auf stationäre Betriebszustände gebracht.

Numerische Ergebnisse für ein spezielles Ofensystem werden mitgeteilt.

РАБОТА РАСПОЛОЖЕННОЙ В ШАХМАТНОМ ПОРЯДКЕ ПАРАЛЛЕЛЬНОЙ СИСТЕМЫ ДОМЕННЫХ ПЕЧЕЙ В НЕСТАЦИОНАРНЫХ УСЛОВИЯХ

Аннотация—Проведено теоретическое исследование оптимальной работы расположенных в шахматном порядке параллельных доменных печей в нестационарных условиях, вызванных изменениями нагрузок. Рассмотрены два различных типа изменений нагрузок. Первый тип состоит из тех изменений, которые немедленно используются системой печей. Для этого типа изменений нагрузок исследуется задача, как по возможности быстрее вернуть систему к стационарным условиям работы после разового изменения нагрузки. Второй тип изменений нагрузки состоит из изменений, которые слишком велики для немедленного использования. В этом случае предусмотрены две стадии: на первой стадии теплосодержание печей доводится до точки, при которой требуемая нагрузка может быть использована, а во второй стадии система возвращается к стационарным условиям работы. Приводятся численные результаты для определенной системы печей.