Uncorrected advance copy of a paper to be presented to the Members of the Institute of Fuel, In the Lecture Theatre of the Geological Society of London, Burlington House, Piccadilly, W.1, on Thursday, February 9, at 6 p.m.

After the Meeting an Informal Dinner will be held at the Café Royal, Regent Street, London, W.1, at 5s. per head, exclusive of liquid refreshment. Members wishing to attend this dinner are asked to notify the Secretary a day or two beforehand.

No publication of this paper, in whole or in part, can be permitted until after February 9.

Additional copies of this paper can be obtained from the Secretary, The Institute of Fuel, 53, Victoria Street, London, W.1.

THE INSTITUTE OF FUEL

The Aerodynamics of Domestic Open Fires

By Professor P. O. ROSIN, Dr.Ing.

I. Introduction.

THE domestic open fire in which so many million tons of coal are burnt yearly, is a combined applicance for heating and ventilation. Part of the heat derived from the combustion of the fuel serves for warming the room and the building and sometimes also for cooking and hot water supply. The other part performs an aerodynamic task. It provides the motive force necessary for inducing the flow of combustion air to the coal, for removing the combustion gases and for conveying large quantities of ventilating air through the room and up the chimney. In any combustion appliance the chemical process of combustion is brought about and governed by streaming, and its intensity is largely controlled by aerodynamic factors-namely, the velocity, amount and distribution of the combustion air. But in the open fireplace a second aerodynamic process is superimposed upon that of combustion ; for the amount of ventilating air, set in motion by the action of the fireplace chimney is many times greater than that of the combustion gases themselves. If, for example, the air in an average living-room be renewed three times per hour, which is by no means excessive, a quantity of air has to be moved which is about 15 times as great as the amount necessary to keep a fire burning in the room, Eight air-changes per hour, which are not rare, correspond to 40 times the quantity of air actually required for combustion. This dual function of the open fireplace creates, therefore, flow problems differing in many respects from those of other combustion appliances. Not only does the aerodynamic factor play a far greater rôle in an open fire than in a closed stove, but it is also more difficult to trace. At the same time those problems deserve special attention in the domestic open fire, because it is so closely linked with the health and comfort of millions of people.

In conversations with Mr. Bennett in 1936, we discussed the possibility that an attempt should be made to attack this problem by making use of models, which have proved such powerful instruments in the study of fluid flow.

Early in 1937, I was entrusted with a research on these lines to be carried through under the auspices of the Combustion Appliance. Makers Association (Solid Fuel) and the Lancashire Associated Collieries, and subsequently the British Coal Utilisation Research Association.

Facilities for the esperimental work were granted to me by the Governing Body and by the Rector of the Imperial College of Science and Technology, Sir Henry Tizard, and by Dr. Lander, then Dean of the City and Guilds College. To carry out model experiments in Professor Lander's department gave me particular satisfaction, because for many years he and I had pursued similar ideas as to the importance of the physical factors in fuel technology and the possible use of models. In 1929, Dr. Lander wrote: [1] " Those concerned with heat problems have cause to look with envy upon the results obtained in aerodynamics through the medium of small scale model experiments."

In the performance of the experiments I was assisted by Mr. M. W. Thring and Mr. G. C. Phillpotts of the staff of the British Coal Utilisation Research Association. The photographic work was done by Captain B. Brandt. Numerous bodies, firms and persons helped me by giving suggestions and encouragement. To all who sponsored and assisted this work I wish to express my sincere gratitude.

The flow problems involved in a fireplace can be classified in four categories :-

(l) The flow of the combustion air to, through or past the fuel bed, and the rising of the hot gases in the fireplace itself. This combustion flow depends upon the kind of grate and fireplace design and on the arrangement of the bed of fuel. It governs the intensity or rate of combustion.

(2) The influx from the room of the cold air and the, estent to which it mixes with the combustion gases in the fireplace. This flow governs the ventilation of a room, and at the same time affects the temperature of the radiating fire-back.

(3) The flow of air and gas in the throat and through the chimney, depending on their design, dimensions and construction. If downdraught occurs, resulting in a smoky fireplace, it is mainly due to this part of the flow.

(4) The flow at the exit of the chimney, depending on the design of chimney pots and influenced by the surroundings and wind currents.

The first three categories, the combustion flow, the ventilation flow and the chimney flow were the objectives of the model experiments, in which water was used as streaming fluid and the process of combustion reproduced by one of solution. The present paper reports in detail on the principles of similarity involved, the calculation of the model and the results obtained with it. Those who are more interested in the practical issues and less in theory and model planning may skip Chapters II and III.

II. Similarity in the Physics of Solution and Combustion.

A. General *Resemblance.*

The combustion of solid fuel is effected in most cases by air streaming through the fuel bed and thereby entering into reaction with the fuel surface. The motion of the air through the fuel bed is caused by the pressure exercised by cold air of greater density against a column of hot combustion gases of lower density. If these two gases of different density are separated from each other above the coal, as shown in Fig. I, the air finds access only from below, thus streaming in its entirety through the fuel bed. The case of Fig. 1 is the scheme of a closed combustion appliance-for instance, a heating stove.

If the system is accessible to the denser air also above the coal (Fig. 2), a greater portion of air enters there, whilst only a smaller quantity flows through the fuel bed. This case corresponds to the open fire with a raised stool-grate. Of the top air only a small portion comes into contact with the fuel or combustible gases and takes part in the combustion.

If the fuel does not rest on a stool-grate allowing the air to enter from below, but on a hearth bottom-grate (Fig. 3), then the whole of the air enters above the fire. This is a special case which, in the whole technique of burning coal, is only found in the open 'fireplace. It appears surprising that enough air should reach the coal to maintain combustion. A comparison with a process of solution may, however, serve to clear up this phenomenon.

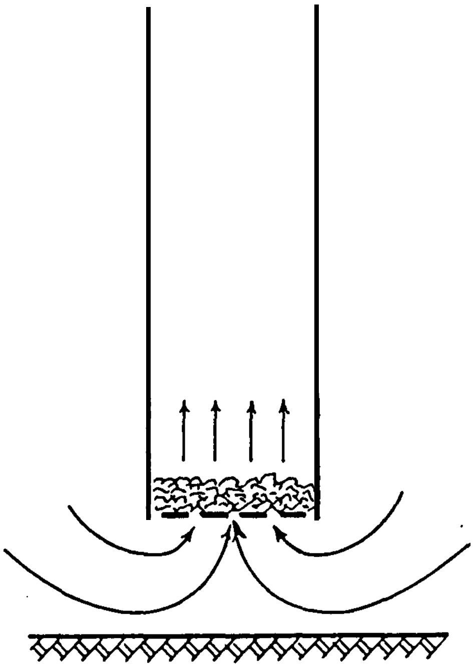

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FIG. 1.

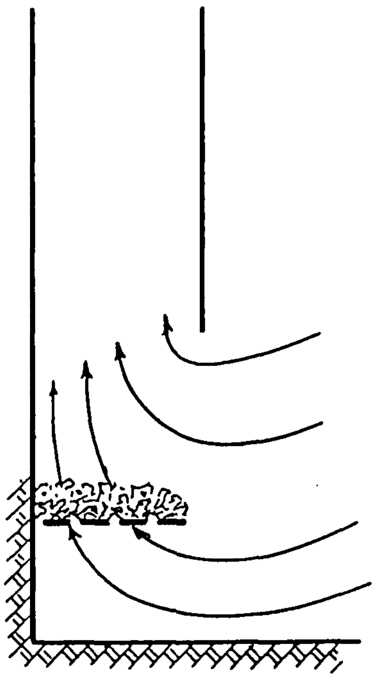

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FIG. 2.

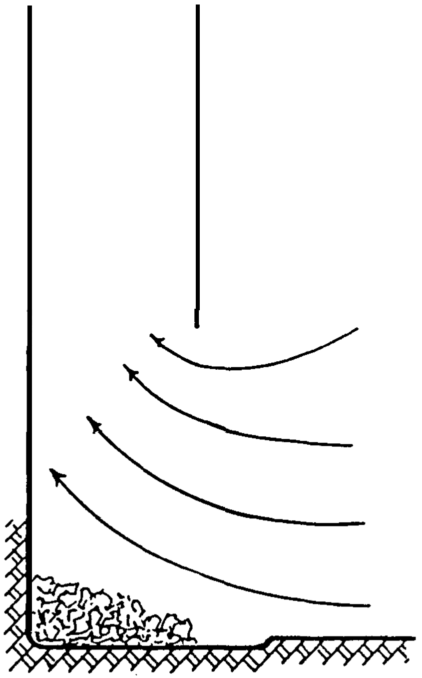

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FIG. 3.

If one brings a bed of salt on a grate to the surface of a water-filled cylinder (Fig. 4), the salt solution of higher density flows downwards and is replaced by an upward current of fresh water which enters the voids of the salt bed at the same rate. The velocity of the process of solution is governed by the velocity of the down-flow. This is an analogous case to the hearth bottom-grate. Although the influx takes place opposite to the down-flow, a lively reaction can nevertheless be maintained, if the differences of density are sufficiently high.

Comparing the processes of combustion and solution, clear definitions must be established. The *solubility* of a solid material in a liquid is defined as the maximum weight which will dissolve in a given quantity of a solvent at a given temperature. This weight is different for different salts in water. There is nothing similar to this for the combustion of a fuel in air. The air can always exchange its total oxygen against combustion products, and the limiting content of combustion products in waste gases is, therefore, constant and independent of the fuel. The so-called *combustibility* of fuels corresponds, not to solubility, but to another phenomenon of solution which has not yet been given much attention, although being of practical importance in chemical technology and of special significance for model tests.

Let us suppose that a certain amount of water streams between the two walls of Fig. 5. In the one wall the surface of a salt body is arranged in such a way as to lie exactly in the plane of the wall. The water streaming past dissolves the salt surface, and the spring is so arranged as to push the salt body exactly in accordance with the rate of solution. The salt surface, providing the solution is uniform, will always lie flush with the wall. The velocity with which the solution proceeds perpendicularly to the surface and the spring pushes the salt forward can be expressed as centimetres per second $\left[\frac{\text{cm.}}{\text{sec.}}\right]$.

Although the solubility of a salt in grammes per litre is a constant at a given temperature, the velocity of the solution can vary. It depends on the velocity and character of the flow, the size of the surface, and the structure as regards density of the salt body. Even with the same waterflow and dimensions of the surface the velocity ' solution may still vary. If the salt has only been .oosely compressed from coarse grains and possesses a porous structure, the solution velocity will be greater than if the body had been briquetted from finely ground powder at high pressures. It is therefore necessary to introduce-in addition to solubility-the new conception of the *velocity of dissolution*, which is an analog} to the *combustibility*, or rate of combustion, of a fuel, and includes within itself the dependence on the aerodynamic factor.

The water streaming past the salt surface in Fig. 5 because the easily combustible fuels contain, as a rule, a higher proportion of volatiles. The evolving gases burn in the space outside the fuel bed, thus saving a corresponding amount of fuel surface which would otherwise be required. Slow-burning low-volatile fuels like coke must therefore offer to the air a larger burning surface. So combustion of such fuels can be maintained if the air passes only over the outer surface of the bed, as is the case in a hearth bottom-grate. The combustion air must stream through a bed of sufficient thickness, and its velocity along the burning surfaces must be high enough to tear up the boundary layer in which the transport of substance takes place by means of the slower process of diffusion. In addition, a higher level of temperature must be maintained in order to accelerate the combustion. The arrangement of the bed, i.e., mainly the ratio between radiating surfaces and total volume, must be such as not to allow

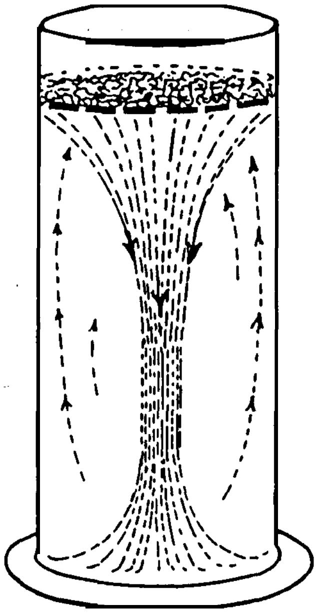

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FIG. 4.

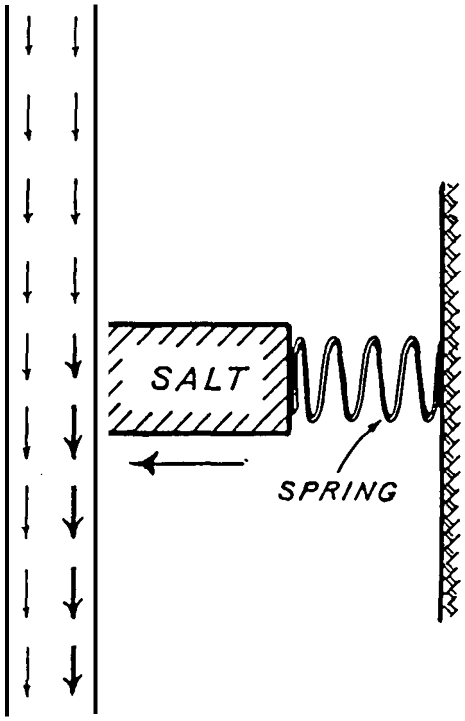

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FIG. 5.

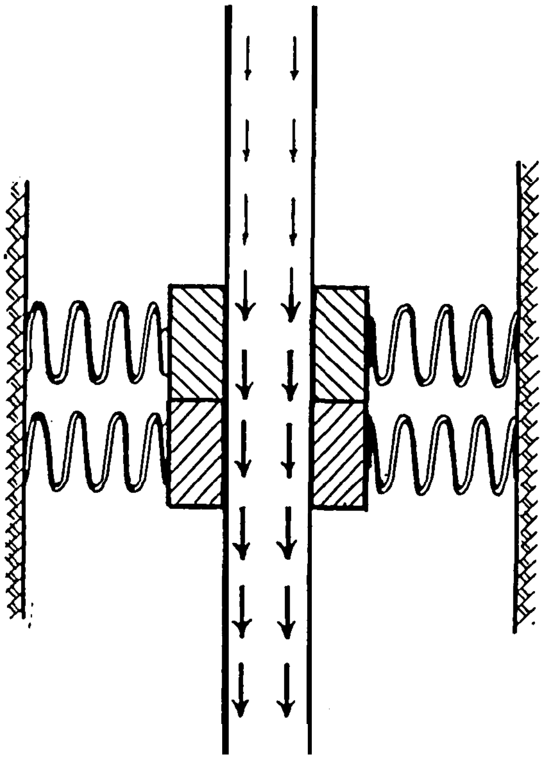

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FIG. 6.

attains a certain salt concentration. If the velocity of dissolution is high enough, the concentration can reach the limit of *the* solubility of that salt, and a saturated solution results. But with a slowly dissolving salt a dilute solution able to dissolve still more salt will stream downward. If, in this case, by a given quantity of water the same weight of salt shall be dissolved in unit time, additional salt surfaces must be arranged as, for example, in Fig. 6. Here the same weight of salt is esposed to the flow, but with the fourfold surface. With a fast-dissolving salt the exposure of additional surfaces would be of no use, because they would only come into contact with an already saturated solution.

A corresponding argument holds for fuels of various combustibility. The same volume of air streaming past the surface of an easily combustible coal burns more fuel, shows a higher CO_2 content, and produces more heat than when passing by the same surface area of a less combustible fuel like anthracite or high-temperature coke. This difference of combustibility is still more marked in practice, its sensible heat content to fall below a temperature level at which the reaction velocity would become too low.

B. *Similarity and Disparities.*

Having introduced an analogy between combustion and solution of which intensive use will be made in the following experiments, the principles of similarity involved must be more rigorously considered. The combustion of a solid fuel in air and the solution of a solid body in a liquid have in common that the reaction takes place at the boundary layer between the solid and the liquid phase. The primary effect of the streaming conditions on the reaction in the boundary layer is, in principle, similar in both cases. The processes themselves are, however, distinct in nature. Not because in one case air is used and water in the other, for both obey the same laws of flow at about constant' pressure, but because combustion is governed by an aerodynamic plus a thermal component, whereas solution—leaving aside the heat of dissolution-is mainly controlled by the hydrodynamic factor alone.

Comparing the two processes the following limitations must, therefore, be taken into account :-

(1) The solution begins at once when the salt comes into contact with the solvent. No process of acceleration exists corresponding to that of ignition. The ignition of a fuel bed or even of a single piece of coal takes place quite irregularly and, as a consequence thereof, the various surfaces burn at different times and with varying intensities, though they may be equivalent from an aerodynamic viewpoint. Neither the process of ignition nor the irregularities in combustion due to it can be reproduced by solution.

(2) The differences in density between air and combustion gases are much greater than those between solvent and solution. The motive forces of buoyancy of hot combustion gases cannot therefore be compared with those of the downdrift of a heavier solution.

(3) The differences in density are due to different causes. With solution the concentration of dissolved material causes the downdrift. With combustion the temperature and not the concentration of the combustion gases causes the buoyancy.

(4) Owing to the rise in temperature the combustion gases expand enormously during the reaction while the volume of the solvent remains practically constant.

(5) The acceleration of the reaction by rising temperatures has a much stronger effect in combustion than in solution. Similarity with solution is therefore restricted to the period of steady combustion at approximately constant temperature.

C. *The Laws of Similarity.*

Full similarity between two chemical systems is only accomplished by :-

(1) *Geometrical Similarity.*—The ratio between any two corresponding lengths of the two processes must be constant. This applies to the measurements of the appliances as well as to the size of the solid participants.

(2) ***Dynamic Similarity.***—The ratio between the forces acting at any two corresponding points of the two systems must be identical. In chemical or physical processes in which a flow occurs, the two deciding ratios are :-

(a) the ratio between 'friction forces and inertia, expressed by the Reynolds number ;

(*b*) the ratio between gravity forces and inertia, expressed by the Froude number.

(3) *Chemical Similarity.*—Although it is not necessary that the participants are identical chemical substances, the numbqr of phases must be the same, and the ratio between the molecular concentrations of all substances participating in the reaction must be identical for any two corresponding points of the two systems.

(4) *Thermal Similarity.*—At any two geometrically corresponding points of the two systems the ratio between heat evolution or input and heat consumption or transfer must be identical. This means also that the proportions of reaction heat, convection, conduction and radiation must concur for any two corresponding points. This includes, that the temperature coefficients of the two reactions be equal.

It is self-evident that neither chemical nor thermal similarity exists between combustion and solution. Geometrical similarity can, of course, be achieved between a coal-burning appliance and a salt-dissolving model. Dynamic similarity requires equal Reynolds Numbers with regard to corresponding friction forces and equal Froude numbers with regard to corresponding gravity forces.

The Reynolds Number (Xc).— If at a given point of a system, in which a fluid flows, v denotes the velocity of flow in $\frac{\text{cm}}{\text{sec}}$, l a characteristic length of the system in cm, and ν the kinematic viscosity of the flowing fluid in Stokes $\frac{\text{cm}^2}{\text{sec}}$, the dimensionless Reynolds Number is

$$Re = \frac{vl}{\nu} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The establishment of the Reynolds Number serves a two-fold purpose :

(1) Identity of Re in two geometrically corresponding points of two different systems is the criterion for hydro- or aerodynamic similarity. Establishing Re for two such points simultaneously fixes the ratio of lengths and velocities in the two systems, since from

$$Re = \frac{v_1 \; l_1}{\nu_1} = \frac{v_2 \; l_2}{\nu_2} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

follows

$$\lambda = \frac{l_1}{l_2} = \frac{v_2 \; \nu_1}{v_1 \; \nu_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

For the mere criterion of similarity it is irrelevant which length is chosen so long as l_1 and 1, are corresponding lengths of the two systems. Any other two corresponding linear dimensions l_i of the two systems must then also fulfil the condition $\lambda = \frac{l_{i1}}{l_{i2}}$! The numerical value of Re is irrelevant in this case.

(2) The numerical value of the Reynolds Number is supposed to characterise a fluid flow, because the thickness of the boundary layer, the formation and stability of eddies, the manner in which the liquid streams round a solid body, the distribution of velocity in a pipe or chimney depend on the ratio between friction forces and inertia of which Re is the numerical expression. For this purpose values of ***1, v*** and ν must be used, which are co-ordinated to the point at issue, for example, the respective diameter of a pipe, the mean hydraulic diameter for rectangular cross-sections, the mean size of particles forming a bed, etc.

The Froude Number (Fr).—In most technical cases of fluid flow the action of gravity can be neglected so that the Reynolds Number alone is a sufficient criterion. That model tests for the determination of the resistance to flow of ships must be based on identical Froude instead of Reynolds Numbers is due lo the fact that the resistance of a Ship moving in water is much more dependent on the surface waves which are caused by gravity than on the friction forces in the water. Usual forms of the Froude Number are :—

$$Fr = \frac{l_1}{t_1^2 \frac{\gamma_1}{\rho_1}} = \frac{l_2}{t_2^2 \frac{\gamma_2}{\rho_2}} \quad . \quad . \quad . \quad . \quad (4)$$

or

$$Fr = \frac{v_1^2}{l_1 \frac{\gamma_1}{\rho_1}} = \frac{v_2^2}{l_2 \frac{\gamma_2}{\rho_2}} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

from which follows

$$\lambda = \frac{l_1}{l_2} = \frac{v_1^2}{v_2^2} \cdot \frac{\gamma_2/\rho_2}{\gamma_1/\rho_1} \quad . \quad . \quad . \quad . \quad (6)$$

where I,, l_2, v_1, v_2 are again corresponding lengths and velocities, t the time in seconds, and $\gamma_1/\rho_1 = \gamma_2/\rho_2 =$

$\frac{\text{specific gravity}}{\text{density}} = g =$ acceleration due to gravity $\left[\frac{cm}{sec^2}\right]$. It follows

$$\lambda = \frac{l_1}{l_2} = \left(\frac{v_1}{v_2}\right)^2 \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

which in the case of ship models is irreconcilable with the condition derived from the Reynolds Number

$$\lambda = \frac{v_1}{v_2} \quad , \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (8)$$

Since the Froude's similarity is more important in model ship tests, the Reynolds' similarity is primarily neglected and accounted for by correction factors. Comparing, however, combustion and solution processes in which the motion of the fluids is caused by the differences of the specific gravity, there is, although the Reynolds' similarity is preponderant for the reaction, no *prima facie* justification for neglecting the Froude Number. When investigating this problem, the form of Fr as given in equations (4) and (5) no longer sufficed. A new Froude Number respecting the special phenomenon of buoyancy or downdrift had to be derived in which the ratio between the forces of inertia and buoyancy instead of gravity was expressed. In it the difference between the density γ_1 of air and γ_1' of gas (or γ_2 of water and γ_2' of a salt solution) plays a part. It is, therefore, according to the principles of dimensional analysis :—

$$f\left(l, v_1, \frac{\gamma_1}{g}, (\gamma_1-\gamma_1')\right) = o \quad . \quad . \quad . \qquad (9)$$

$$f\left(\left[cm.\right], \left[\frac{cm.}{sec.}\right]^x, \left[\frac{gr.\ sec.^2}{cm.^4}\right]^y, \left[\frac{gr.}{cm.^3}\right]^z\right) = o \qquad (10)$$

giving

$$x = -2$$
$$y = -1$$
$$z = +1$$

The Froude Number for buoyancy processes is therefore

$$Fr = \frac{lg}{v^2} \cdot \frac{\gamma_1 - \gamma_1'}{\gamma_1} \quad . \quad . \quad . \quad . \qquad (11)$$

For similarity between the phenomena of rising gases and sinking solutions the following equation must hold :—

$$Fr = \frac{l_1 g}{v_1^2} \cdot \frac{\gamma_1-\gamma_1'}{\gamma_1} = \frac{l_2 g}{v_2^2} \cdot \frac{\gamma_2-\gamma_2'}{\gamma_2} \qquad (12)$$

or

$$\lambda = \frac{l_1}{l_2} = \frac{v_1^2}{v_2^2} \cdot \frac{\gamma_1}{\gamma_2} \cdot \frac{\gamma_2-\gamma_2'}{\gamma_1-\gamma_1'} \quad . \quad . \qquad (13)$$

Since at the same time the condition (3) derived from the Reynolds Number must hold, it follows

$$\lambda = \frac{l_1}{l_2} = \frac{v_2}{v_1} \cdot \frac{\nu_1}{\nu_2} = \frac{v_1^2}{v_2^2} \cdot \frac{\gamma_1}{\gamma_2} \cdot \frac{\gamma_2-\gamma_2'}{\gamma_1-\gamma_1'} \qquad (14)$$

which is fulfilled for

$$\frac{v_2^3}{v_1^3} = \frac{\nu_2}{\nu_1} \cdot \frac{\gamma_1}{\gamma_2} \cdot \frac{\gamma_2-\gamma_2'}{\gamma_1-\gamma_1'} \quad . \quad . \quad . \qquad (15)$$

$$\frac{v_2}{v_1} = \sqrt[3]{\frac{\nu_2}{\nu_1} \cdot \frac{\gamma_1}{\gamma_2} \cdot \frac{\gamma_2-\gamma_2'}{\gamma_1-\gamma_1'}} = \frac{l_1}{l_2} \cdot \frac{\nu_2}{\nu_1} \, * \qquad (16)$$

* For the conditions of similarity, the Reynolds and Froude Numbers can be combined in various ways. A useful combination is, for instance,

$$Fr.\, Re^2 = \frac{lg}{v^2} \cdot \frac{\gamma-\gamma'}{\gamma} \cdot \frac{v^2 l^2}{\nu^2}$$
$$= \frac{l^3 g}{\nu^2}\left(1-\frac{\gamma'}{\gamma}\right) = Gr$$

which is the so-called Grashof Number. Similarity is obtained if either the Grashof and Froude or Grashof and Reynolds Numbers are equal.

As will be shown in the part dealing with the calculations of the model, it is not impossible at least to approximate to this condition with a model representing the flow of the combustion gases by that of a solution. If full equality of the Froude Numbers cannot be obtained, the acceleration of the flow due to buoyancy in combustion is dissimilar to that due to downdrift in solution, and the moving forces of the two processes are incomparable. Nevertheless, similarity of flow is established if by other means the motion of air and gas, and of water and solution, are made such as to possess equal Reynolds Numbers. It follows :-

(1) A resemblance exists between combustion and solution. Both are diffusion processes, the course of which is determined alike by aerodynamic factors-namely, the character of flow, thickness of boundary layer, etc.

(2) Neither chemical nor thermal similarity exists between combustion and solution, because the thermal factor is wanting in solution.

(3) Full dynamic similarity exists in some cases when both the respective Reynolds and Froude Numbers can be made equal.

(4) Partial dynamic similarity as regards the flow characteristics exists between all corresponding points with equal Reynolds Numbers.

That neither chemical nor thermal similarity exists between combustion and solution must not lead us to condemn the method as inadequate. It is not the purpose of solution experiments to imitate combustion. Combustion is a process in which aerodynamic and thermal phenomena are inseparably connected. Combustion experiments will never throw light on the relative effect of either of these influences. But by solution experiments the aerodynamic component can be isolated and its influence brought home. In many cases of applied combustion the aerodynamic factor is predominant and the quantitative knowledge of its action is of great practical value. The investigation of solution processes in similar models is probably the only, and certainly the cheapest and most effective way of studying the influence of the aerodynamic element.

Since, owing to the chemical and thermal disparity the dynamic similarity often does not extend over the whole course of both processes, the Reynolds and Froude criteria of reference should always be established for those corresponding points on the investigation of which a model esperiment is focused.

III. The Open Fireplace Model.

A. *Objectives of Model Experiments.*

The aim of model physics is to reproduce in handy models processes of which the full scale experimental investigation—because of their complexity—would be either impossible or far too expensive and which also cannot be dealt with mathematically. Model tests can, therefore, serve a threefold purpose :-

*(I) To make visible to the eye and accessible to the photographic lens total or partial phenomena and thus enable us to study them quantitatively. Such phenomena are in our case the flow of air and gas in fireplaces and chimneys.

(2) To study the influence of constructional details upon the whole phenomenon by altering or exchanging individual parts. For example, in our problem to investigate the effect of different firebacks, chimney-breasts, throats, etc.

(3) To establish mathematical relations between criteria that are characteristic for the process at issue. For the

open fire, for esample, the relations between the draught and the fuel consumption, or more scicntifically espressed, between the flow characteristic in thc throat and the rate at which thc coal burns in thc gratc.

The results obtained with a model arc valid for all similar processes, irrespective of size, so long as the postulate of equal criteria is fulfilled. A model thus supplies not only a singular solution, but a multiplicity of solutions of the order of similar cases. Unfortunately, complete similarity is to be realised only in thc rarest cases. Mostly one must content oneself with incomplete similarity in which only the main process takes place similarly, secondary processes being dissimilar, or with approximate similarity if the postulates of similarity cannot be quite fulfilled. Notwithstanding, also in such cases which form the majority, model science has stood the test as a powerful weapon for the engineer.

One must, however, always endcavour to estimate the inaccuracies and errors arising out of incomplete or approximate similarity. Here lie at the same time the weakness and the strength of applied similarity. First, one must collect all the physical and chemical criteria involved in the process, and then establish the limitations-due to incomplete congruence of the fundamental criteria-of the transferability of model results. This compels us to think down to the last details of a process, for without the most intimate acquaintance with its dynamics the fruitful application of model technique is unthinkable. Because complete similarity is almost *never to* be attained, only he, who by long experience has gained a sovereign perception of the nature of a process can rightly judge the limits. Never can a model law for a new task be derived and the results transferred without the deepest penetration into the essence of the phenomenon. Without this, even thc best command of thc proper science of similarity and dimensions is likely to fail. We must, therefore, be on our guard lest the theory of dimensions be confused with the science of models. Once the magnitudes deciding the course of a process are known, the derivation of the special model law as demanded by the theory of dimensions is a relatively simple technique—but to classify the governing magnitudes and to bridge the gaps arising out of incomplete and approximate similarity means scientific insight as well as engineering experience with the process under study.

The classical physics of similarity starts from the question : " When are two processes dynamically similar ?" and answers : " If certain dimensionless groups of variables (criteria and parameters) governing the process are identical." This branch aims at determining in a handy design the numerical relations between those dimensionless groups, which relations can then bc transferred to all similar processes that possess identical criteria. The apparatus with which these results are obtained is not a model proper. It is just one selected size excelling only by more conveniently lending itself to investigation.

But for the engineering branch, model technique has still another meaning-namely, to make happenings visible and measurable at all, and thus to permit the observation in small scale models of occurrences that otherwise are invisible, incalculable and immeasurable. Here, the mathematical correlation of criteria is an issue secondary to the possibility of making the phenomena perceptible to the eye and the photographic lens. This refers in particular to all large scale combustion phenomena in which gaseous flow is involved. The model tests of applied combustion research arc, therefore, less akin to the methods of similarity physics-adopted, for example, in heat conduction--than to those used in the aeronautic and hydraulic laboratories.

From this discrimination the scepticism can be understood which clicmists feel sometimes unable to conceal regarding the application to problems of combustion of model mechanics in general, and solution processes in particular. They often do not conceive that it is not the thermo-chemical process of combustion which is to be reproduced by solution, but only the influence on it of the aerodynamic component, and they have difficulties in understanding that the flow of a solution can, in principle, bc similar to that of combustion gases. Yet it is hoped to prove by this report, that the appropriate application of models will convey such a concrete impression as would not bc obtainable by any other method of investigation. Nothing can better describe the meaning and object of model tests applied to open fires than what Benjamin Thompson, Count of Rumford, wrote in one of his famous essays of Chimney Fireplaces : (2) " Both air and water being transparent and colourless fluids, their internal motions arc not easily discovered by the sight ; and when these motions are very slow, they make no impression whatever on any of our senses, consequently they cannot bc detected by us without the aid of some mechanical contrivance : but where we have reason to think that those motions exist, means should be sought, and may often bc found, for rendering them perceptible."

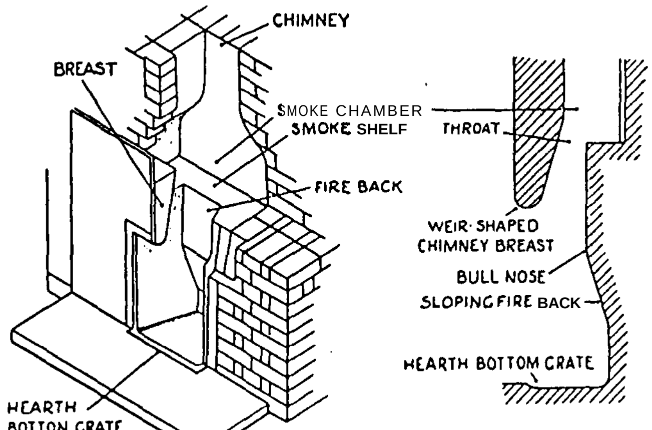

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FIG. 7.

B. *The Calculation of the Model.*

There exist many designs of fireplaces which could have served as prototype for the model. After a comprehensive survey of the existing modern constructions the fireplace as recommended by the Building Research Station was found to incorporate the essential parts in their purest form and configuration. Fig. 7 shows a diagram. This construction is founded upon the prescriptions given by Rumford.(2) He introduced the wedge-shaped fireplace opening towards the room, the forward sloping firebrick back with smoke shelf and the smoothly curved weir-shaped chimney-breast. After more than a century of application his prescriptions were successfully revived and revised by Dr. A. F. Dufton, of the Building Research Station. I am indebted to the Department of Scientific arid Industrial Research and to the Controller of H.M. Stationery Office for permission to reproduce this diagram.

Rumford's great discovery was that the chimney throat must be narrow in order to obtain an orderly flow and cure smoky chimneys. He rightly recognised that the throat was the fundamental point of an open fireplace. The throat must, therefore, be made the point of reference for the similarity. The full size fireplace and the model must have, in the first place, equal Reynolds Numbers in the throat.

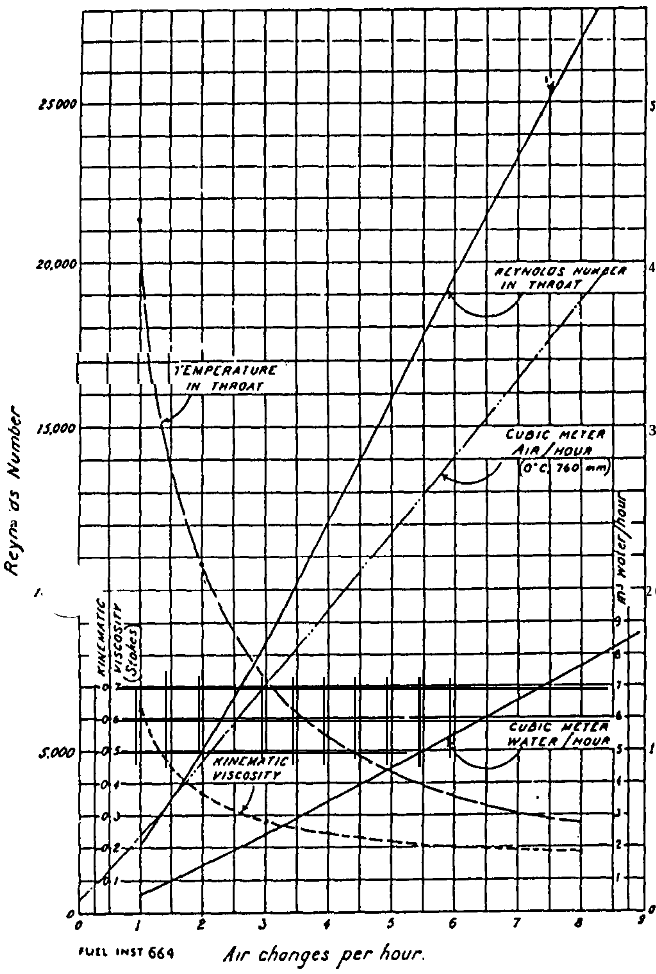
C in assumptions had to be made for the calculation of the Reynolds' Number. They were derived from Dr. M. Fishenden's ([3]) investigations:

Size of room:

16 ft. 8 in. × 11 ft. 5 in. × 8 ft. 8 in. = 1,650 ft.3 = 47m³.

Coal consumption:

2.5 lb./hr. = 1.13 kg./h.



. FIG. 8.

Calorific value of coal:

13,500 B.Th.U./lb. = 7,500 k.cal./kg.

Heat liberated:

2.5 × 13,500 = 33,700 B.Th.U./hr. = 8,500 k.cal./hr.

Heat emitted by radiation into the room and convection to the fireplace surroundings: 25 per cent. of liberation.

Heat carried away into the throat by gases:

0.75 × 33,700 = 25,300 B.Th.U./hr. = 6,370 k.cal./hr.

Cross sectional area of throat:

15.75 x 3.94 in. = 62 in.² = 0.04m².

For the throat of rectangular shape, the Reynolds Number is

$$Re = \frac{4m_1 v_1}{\nu_1} \quad \ldots\ldots \qquad (17)$$

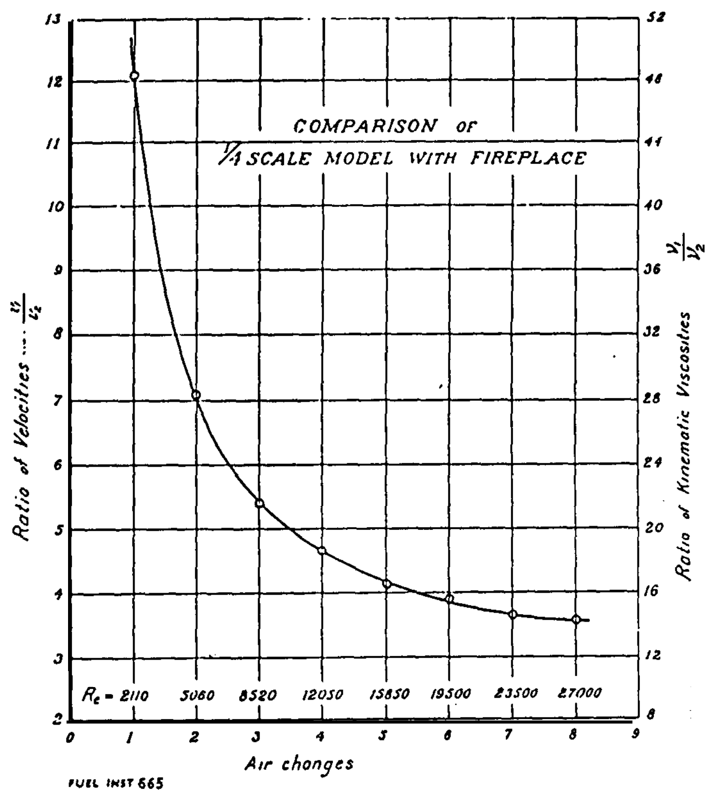


FIG. 9.

where

$$m = \text{mean hydraulic depth} = \frac{\text{area of cross-section}}{\text{perimeter}}$$

$$m_1 = \frac{62}{2\,(15.75 + 3.94)} = 1.575 \text{ in.} = 4 \text{ cm.} \quad (18)$$

Table I shows the calculation of the Reynolds Number in the throat as dependent on the number of air-changes in the assumed room.

TABLE I

1	2	3	4	5	6	7	8	9	10	11	12
Number of air-changes	Waste gas + air. nm³/hr.	Heat content of waste [illegible] / nm³	Mixing temperature. °C.	Actual volume in throat. m³/hr.	Kinematic viscosity of mixture. cm²/sec.	Velocity of gas in throat of fireplace. cm./sec.	Reynolds Number.	Velocity of water in throat of model. cm./sec.	Quantity of water. m³/hr.	Velocity ratio gas/water.	viscosity ratio gas/water.
0	9.4	677									
1						80	2,090	7.	0.61	11.8	47
2	47 94	135 68	212 398	116 167	0.615 0.355	116	5,225	17	1.53	6.8	27
3	141	45	144	216	0.282	150	8,480	39	2.48	5.4	22
4						183	12,130	51	3.54 4.62	4.2 4.6	19
5	235 188	34 27	172	263 310	0.241 0.218	215	15,780				17
6	262	23	62	356	0.203	247	19,450	63	5.69	3.9	16
						281	23,250	76	6.80	3.7	15
3	329 376	19 17	54	404 450	0.193 0.185	313	27.100	88	7.92	3.6	14

The scale of the model was chosen as one-quarter of the size of the actual fireplace. The mean hydraulic depth of the model throat is, therefore, 1 cm. (about 0.4 in.), and, since the kinematic viscosity of water at 10° C. is 0.013 stokes, it follows :-

$$Re = \frac{4\,v_2}{0.013} = 308\ v_2\ (v_2 \text{ in cm/sec.}) \quad . \ . \ (19)$$

$$v_2 = 0.00325\ Re\ \left[\frac{\text{cm.}}{\text{sec.}}\right] \quad . \ . \ . \ . \ . \ (20)$$

The area of the cross-section of the model throat is 0.1 x 0.025 m^2, and the quantity of water in the model is

$$Q\ (\text{water}) = \frac{v_2}{100} 0.0025 \times 3{,}600 = 0.09 v_2 \quad \left[\frac{m^3}{hr.}\right]$$

$$= 0.2925\ Re\ 10^{-3} \quad \left[\frac{m^3}{hr.}\right] \quad . \ . \ . \ (21)$$

Or, if the flow of water in m^3/hr. is measured in the model.:

$$Re = 3{,}420\ \ Q\ (\text{water}) \ldots . \quad (22)$$

The respective figures of the velocity and quantity of water are also given in Table I. The column 11 contains the ratio between the gas velocity in the fireplace and the water velocity in the model. At medium air-changes, the water velocity is only one-fifth of the actual velocity in a fireplace throat. This *means* a specific advantage of such models, because the reduced velocity greatly facilitates the observation.

The various relations between air-changes, air quantity, throat temperature, viscosity, Reynolds Number, and quantity of water are shown in the graph of Fig. 8 ; whilst Fig. 9 shows the ratio between viscosities and velocities at various air-changes.

The calculations prove :-

(1) The flow in the throat of a model designed and operated on these lines is similar to that in the throat of an actual fireplace providing, of course, that the temperature differences between gas and air across the throat are not excessive.

(2) Similarity of the air flow to the coal and into the fireplace also can nearly be attained. The viscosity of air at 20° C. is 0.151, that of water 0.01 stokes ; and it is, therefore, according to equation (3)—

$$\frac{v_1}{v_2} = \frac{l_2}{l_1} \cdot \frac{\nu_1}{\nu_2} = \frac{0.151}{4 \times 0.01} = 3.78 \quad . \ . \ (23)$$

which corresponds to the values of Table I for more frequent air-changes.

(3) The flow of the hot combustion gases between the fire and the throat, particularly near the fire, cannot be similarly reproduced by the flow of water, owing to the variation in viscosity and density which the gas undergoes. Similarity with the flow of the hot gases would require a much bigger ratio of $\frac{v_1}{v_2}$. The actual flow of the hot combustion gases along the fireback is therefore less turbulent than that shown by water in the model. The difference is, however, of no great significance in this range of Reynolds Numbers.

The foregoing refers to the similarity between the flow of air and gases in a fireplace and of water in the model. If, in addition, the production of combustion gases is to be imitated by the production of a salt solution, it must be examined how far the downdrift of the solution is comparable with the buoyancy of the gases, i.e., how far the postulate of equal Reynolds and Froude Numbers of equation (16) can be fulfilled. For this purpose a small heap of coke freely burning in the open air may be compared with one of salt arranged at some point of the surface of a big water reservoir. For an approximate calculation. the following data are sufficiently accurate :-

(1) Solubility of sodium chloride in water at 10° C. :- 35.7 grammes per 100 grammes of water.

Density of water :

$$\gamma_2 = 1000\ \text{kg./m}^3$$

Density of the saturated solution at 10° C. :

$$\gamma_2' = 1.205\ \text{gr./cm}^3 = 1{,}205\ \text{kg./m}^3.$$

Absolute viscosity of the saturated solution at 10° C.

$$\eta = 0.022.$$

$$\text{Kinematic viscosity } \nu_2 = \frac{\eta}{\gamma_2} = \frac{0.022}{1.205} = 0.018 \text{ stokes.}$$

(2) Assumed temperature of gas/air mixture leaving the coke bed : 1000° C.

Density of air at 10° C. . . . ... $\gamma_1 = 1.25\ \text{kg./m}^3$

Density of gas at 1000° C. . . . $\gamma_1' = 1.32 \frac{273}{1.273}$

$$= 0.283\ \text{kg./m}^3$$

Kinematic viscosity of gas at 1000° C. $\nu_1 = 1.58$ stokes.

v_1 and v_2 denote the respective velocities with which the gases and the solution leave the beds. According to equation (16) it is-

$$\frac{v_2}{v_1} = \sqrt[3]{\frac{\nu_2 \cdot \gamma_1 \cdot (\gamma_2 - \gamma_2')}{\nu_1 \cdot \gamma_2 \cdot (\gamma_1 - \gamma_1')}}$$

$$= \sqrt[3]{\frac{0.018 \times 1.25 \times (1.205 - 1.000)}{1.58 \times 1{,}00 \times (1.25 - 0.283)}}$$

$$= \sqrt[3]{0.00302} = 0.145 \ \ldots . \quad (24)$$

$$\frac{v_1}{v_2} = 6.9 \ . \ . \ . \ . \ . \ . \ . \quad (25)$$

The velocity of the rising gases would be seven times as great as that of the sinking solution. Column 11 of Table I shows that with low air-changes the velocity ratio between the fireplace and. the model is of the same magnitude. Consequently, the downdrift from a model grate of a saturated salt Solution gives a visual image similar to the rising of hot gases from a coke-burning grate.

The second condition of equation (16) leads to

$$\frac{v_1}{v_2} = \frac{l_2 \cdot \nu_1}{l_1 \cdot \nu_2} \quad . \ . \ . \ . \ . \quad (26)$$

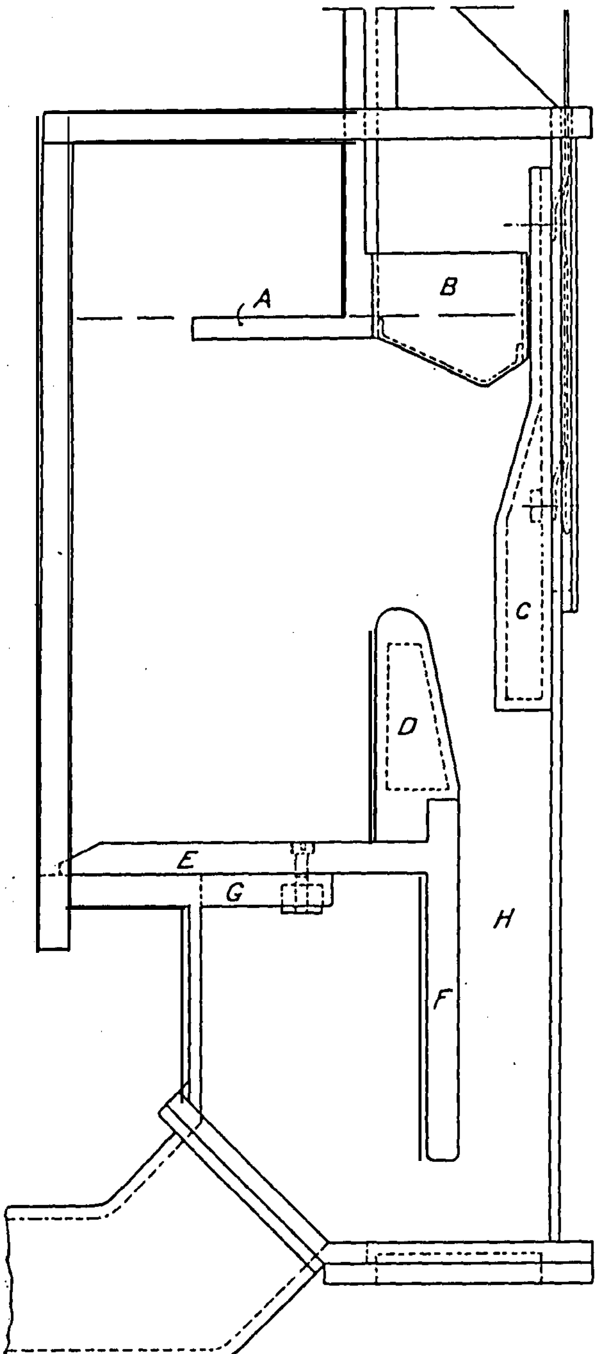
$$\frac{l_1}{l_2} = 0.145\ \frac{1.58}{0.018} = 12.75 \ \ldots \quad (27)$$

which means that to obtain also dynamic similarity between the forces of buoyancy and downdrift, the reduction of scale should be about 12 : 1 and not, as chosen, 4 : 1. But this is of no significance for our purpose, because neither is the motive force of downdrift required to replace the chimney draught and operate the model nor does the time matter in which the solution covers the distance between the grate and throat. What alone matters is :-

(1) Similarity of flow between the combustion and ventilation air in an open fireplace and the water in the model.

(2) Similarity of the motions of hot gases relative to the Surrounding air, and of a salt-solution relative to the Surrounding water. Both are accomplished in the model. This is the more so since the experiments showed the rate of combustion or solution to be largely unaffected by the rate of flow in the throat. Combustion and ventilation flow proved to be almost independent of each other.

On the other hand, the energy of motion of the ventilation flow produced in a fireplace by the combined action of the difference of density and the chimney height cannot be similarly copied by the solution of salt in a model. The water flow in the model representing the air flow must, therefore, be produced and controlled by other means. Since the model, in order to make use of the downdrift of a heavier solution in water, must work upside down, the simplest way of producing a flow is, of course, to let



FUEL INST. 660

FIG. 10.

the water stream through the model under the natural action of gravity and to regulate its outflow. In point of fact, after a long bewilderment as how to produce a similar fireplace model, the idea of turning' the whole arrangement upside down removed the difficulties all at once.

C. *Construction of the Model.*

The variables of which the interactions were to be studied in the model, are :-

(1) Number of air-changes.

(2) Design of grate.

(3) Distance between the grate and throat.

(4) Shape and position of the fireback.

(5) Shape and position of the chimney-breast and canopy.

(6) Width of the throat.

The grate, fireback and chimney-breast in the model had, therefore, to be movable and exchangeable.

On the strength of previous experience ([4]) the model was built entirely of colourless, transparent celluloid plates, 0.1 in. thick, which were homogeneously welded together by means of acetone.* Fig. 10 shows a side elevation. A, a plate representing the floor level is fixed to the grate *B*, which can be lowered or raised. C is the Rumford fireback sliding by means of a spring tongue

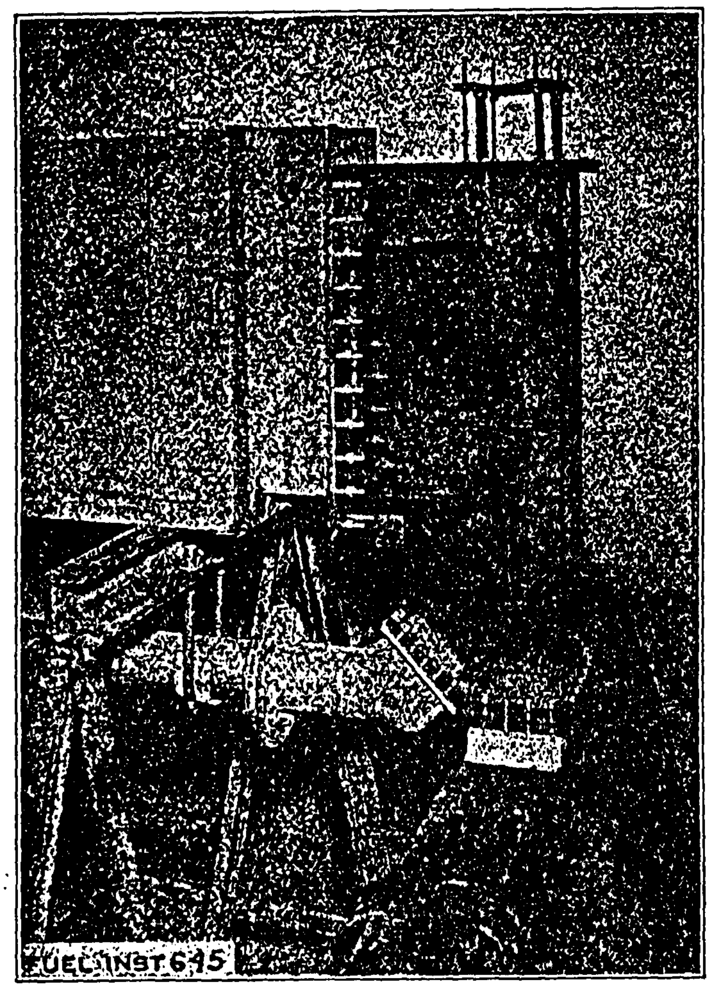


FIG. 11.

in a vertical groove of the wall. *D* is the exchangeable chimney-breast fitted on the angle *EF* which can be moved along the plate *G* thus widening or narrowing the throat. Since only the influx into the fireplace of the air was to be studied, the model was limited at about breast-level by the plate *E*. The chimney *H* is long enough to ensure the undisturbed observation of peculiarities of flow produced by the throat.

Fig. 11 shows a photograph of the model in working position, but without a fireback. The model is a two-dimensional representation of a fireplace as shown in Fig. 7, whilst the wedge-shaped opening into the room, the lateral contraction into the chimney of the smoke chamber and any chimney bends in the third dimension have been neglected. This does, however, not impair the basic features.

* I wish to acknowledge the help of Mr. H. Breitling in the construction of the model.

It being imperative for the operation of such models to have a perfectly uniform and undisturbed influx, the model is, by a lead sheet connection, fitted to a 12-ft. long wooden trough. From a big open tank the level of which is kept constant by an overflow, the water streams into the trough and the flow is smoothed out and streamlined by a honeycomb design. After it, an overflow serves to adjust the level to the respective position of the top-plate *A*, and the disturbance caused by this overflow is smoothed out again by a second honeycomb. The water thus enters the model at a perfectly constant rate with a uniformly streamlined flow. The water leaves the model through a 2½-in. pipe in which the flow is measured by means of orifices. The rate of flow is regulated at the end of the pipe by a main shutter valve for coarse and two side valves for fine regulation. Fig. 12 shows a photograph of the whole arrangement. Light is transmitted through the model by strong bulbs behind it.

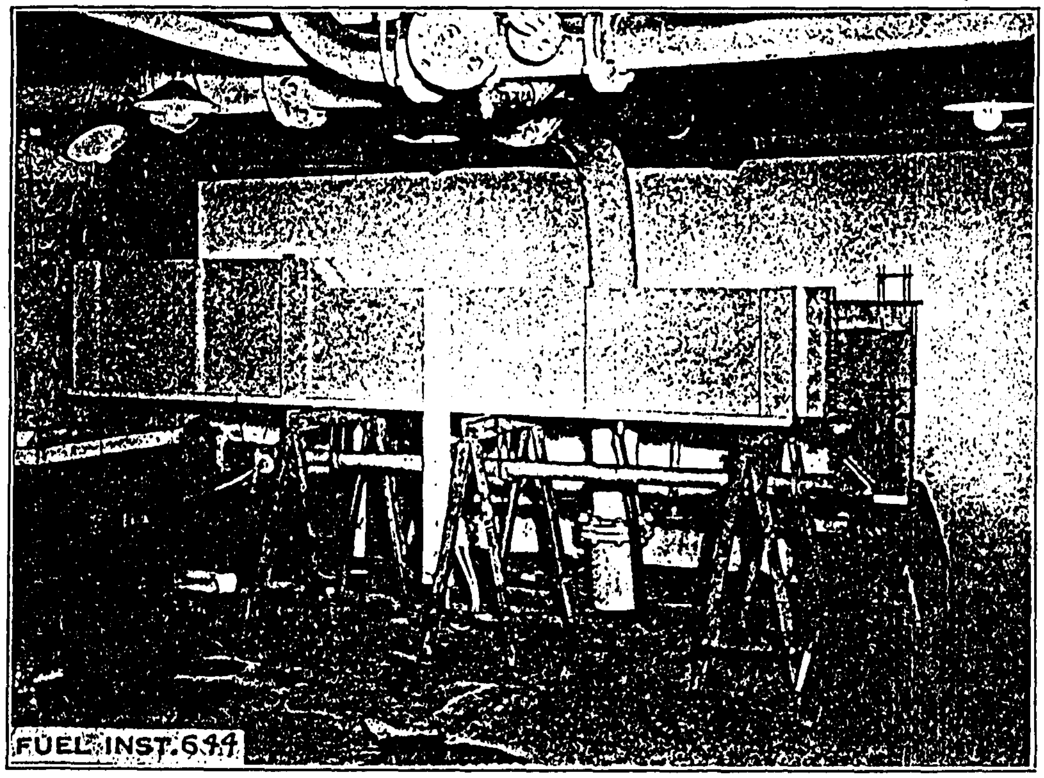


FIG. 12.

D. *Performance of Experiments.*

The *two* main objectives of the investigations were :-

(1) To obtain pictures of the flow of air entering the grate and the fireplace ; of the combustion gases streaming along the fireback ; and of air and gas streaming through the throat.

The direction and intensity of the flow entering the fireplace at various levels were made visible by thin flow lines of dye of the same density as water which were introduced through adjustable thin nozzles, the entrance velocity being made to conform with the respective water velocity. These flow lines could easily be observed and measured. They were sketched, photographed and cinematographed. The downward motion of the salt solution from the grate along the fireback, made visible by using briquettes of coloured salt, was photographed and cinematographed as well.

(2) To study, by the rate of solution, the relations which may exist between the rate of combustion or fuel consumption and the chimney draught, both in the hearth bottom and stoolgrate. This was carried out by recording the decrease of weight of a salt bed on the grate exposed to various flows under varying conditions and fireplace dimensions. It required, first of all, the manufacture of homogeneous, slow-dissolving salt-briquettes, the making of which is described in Appendix I. Appendix II contains a description of the details of such solution experiments.

IV. The Flow of Air and Gases in Open Fireplaces.

A. *The Flow* of Air *into* the *Fireplace.*

The model works under simplified conditions in so far as the influx of the water takes place uniformly through one large opening opposite the fire. This would correspond to a room with an open door or window opposite the fireplace. It is known that in practice such an arrangement should be avoided in order to prevent cross-draught through the room. But the model is not supposed to show the 'air flow through the *room*. *Its* size is such as only to represent a section through the immediate vicinity in front of a fireplace, where the many disorderly currents, arising out of the various openings and leakages through which fresh air enters a room, have already gathered into one uniform stream of definite direction. It must, therefore, be borne in mind, that the lateral components of the air flow, i.e., the turning into the fireplace of air currents reaching it from both sides, cannot, and were not intended to, be seen in the model.

Figs. 14 to 19 show photographs of flow lines at various levels :-

(*a*) at a low velocity corresponding to one air-change per *hour* (*Re* = 2,100) where the flow is laminar ;

(*b*) at a high velocity corresponding to 7.9 air-changes per hour (*Re* = 26,700) where some of the flow lines manifest turbulence.

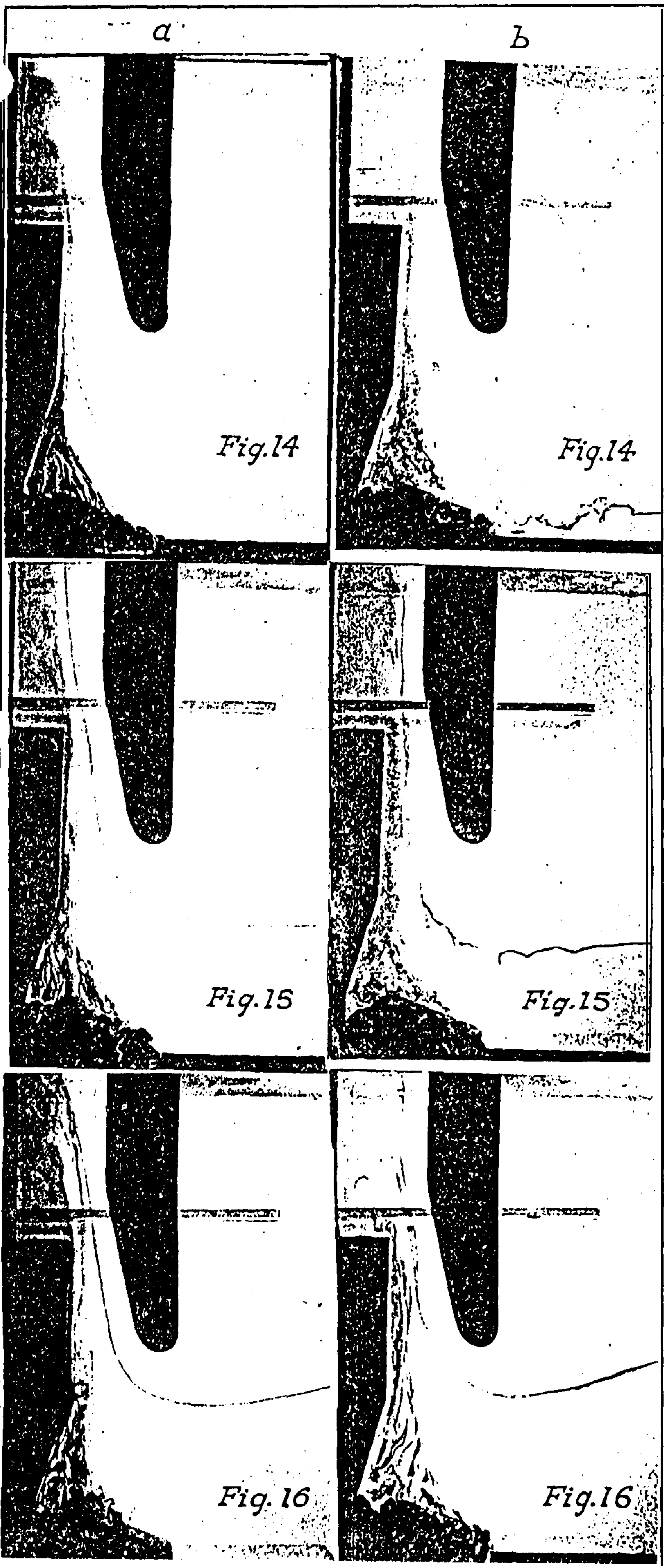
Three observations are obvious at once :-

(1) The combustion gases cling closely to the fireback and the rear wall of the chimney.

(2) There is a strong eddy formation above the horizontal smoke-shelf in which more air becomes entangled at high velocity.

(3) There is much stratification in the chimney, the air from higher levels travelling preferentially up the front wall.

Fig. 20 is a complete flow picture with all flow lines copied from direct observation of the model. The left side refers to a low velocity of one air-change, the right side to a high draught at nearly seven air-changes per hour. Most of the lower air, moving along the floor, turns upwards before reaching the hearth bottom-grate. The fire in a hearth bottom-grate, therefore, burns in an almost dead space sheltered by the sloping back and quite unaffected by the flow of the ventilation air. The density of the flow lines increases as the chimney-breast is



approached, clearly indicating that the chimney-breast is of particular aerodynamic importance. At about shoulder-level only a part of the air streams downward and enters the chimney. The remainder rises along the wall of the room and circulates round the ceiling. In the chimney itself two eddy-fields make their appearance. The one above the smoke-shelf, the other further up the chimney at the inner side of the breast. The detailed discussion of these eddies will follow later. At high velocity the air-flow is pulled upwards whereby the dead space in which the fire burns is enlarged and a backwards eddy produced. More ventilation air strikes and chills the fireback and the combustion gases. The maldistribution of flow a'nd temperature is maintained even at high velocities. The shelf eddy is intensified and diluted with air. These flow pictures indicate already that with a hearth bottom-grate a strong chimney draught cannot be espected to increase the burning rate.

The pictures show further that, unless the inlet into a room of fresh air is near the ceiling, the ventilation by means of an open fire is not altogether ideal. If, in particular, the air enters the room near the floor, as by a gap below a door, then one's legs will be bathed in fresh air whilst the breathing organs are in a region of less fresh air, circulating by itself. It follows that the statement of, say, four air-changes per hour does not always imply that the air in a room is actually renewed four times an hour. It only indicates that a quantity corresponding to four times the volume of the room is streaming up the chimney. Yet much of the air in the upper part of the room may be found to form a stagnant zone circulating in itself. One of the great faculties of the open fire, to procure ventilation of a room, is thus often not adequately esploited, and the current of air streaming through the lower part of a room may become such a stiff breeze as to verify the caustic description: "You are grilled in front and your teeth chatter behind."

Whilst Fig. 20 only showed the direction of the airflow, Fig. 21 shows its relative intensity at the various points by means of observed figures of the velocity in cm./sec. The highest air velocity in front of a fire occurs at knee-level, the 9 cm. in the model corresponding to 36 cm. or about 14 in. above floor-level of an actual fireplace, which is the reason why one has sometimes the sensation of cold feet. The velocity of flow naturally increases as the air turns inside the throat, particular acceleration being undergone by the air that streams round the chimney-breast. In the throat itself the velocity is about sis times that of the entering air. This once more accentuates the great aerodynamic importance of the chimney-breast and throat.

Fig. 22 shows the result of diminishing the fireplace opening by either lowering the chimney-breast or by a canopy. The conspicuous feature is the pressing down of the air-flow towards the grate and the fireback, thus restricting the dead space in which the fuel burns. It must be expected, that by reducing the height of the fireplace opening the fuel will be more exposed to the air flow and the. rate of burning increased. This leads to the important question of how, in the different grates, the air is brought into contact with the fuel.

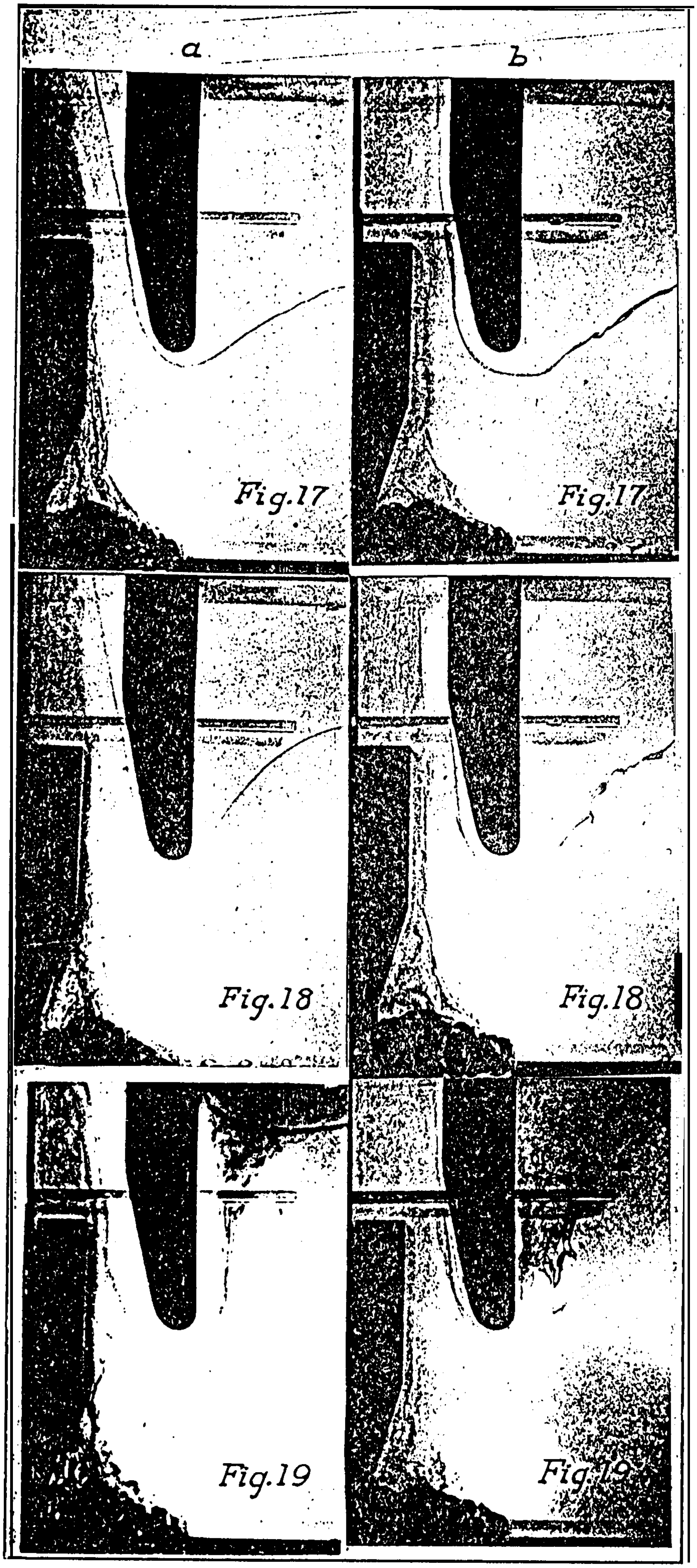
The *hearth bottom-grate* which was introduced about 40 years ago and is now widely used for burning bituminous coal, differs fundamentally from bar- and stool-grates. Obviously, in the hearth bottom-grate the air does not stream through the fuel bed, but approaches it from above as shown in the diagrams. The process is identical with that of the salt solution described in Fig. 4. The access of air to the coal is therefore restricted to the rate necessary to replace the combustion gases leaving it. Hence, the rate of combustion is not controlled by the air-flow, as in other combustion appliances, but the air-flow is controlled by the rate of combustion, which is, in this case, exclusively a function of the nature of the fuel, its size, arrangement and temperature. This will be dealt with more quantitatively in Chapter V.

In the raised *stool-grate* as opposed to the hearth bottom-grate, most of the floor air travels through the fuel bed blowing the fire. The difference between the two constructions can easily be seen in the photographs Figs. 23*a* and 236. The higher the velocity, the greater the proportion of combustion air which is forced through the fuel bed, and the faster the rate of burning. Here the rate of burning is controlled by the intensity of the airflow. It follows that in this type of grate the rate of burning can easily be regulated by a good fret to cut off or adjust the air supply under the fire.

B. *The Flow of the Combustion Gases and the Shelf.*

A glance at the photographs shows that the rising combustion gases cling closely to the fireback. This is brought about by their own buoyancy, and by the ventilation air pressing them back. It occurs the more the stronger the influx of the air. The influx is weakest near the grate, leaving the flame more space, but at higher levels the combustion-gas is reduced to a thinner layer streaming along the fireback. The same phenomenon could be observed with any design of firebacks, and must be kept in mind in any investigation of the most favourable shape, position and manufacture of firebrick-backs.

By the sudden enlargement of the throat above the horizontal smoke-shelf a violent breaking-away eddy is formed in the direction which is marked in Fig. 20. The shelf-eddy destroys the uniformity of flow by whirling downward the combustion gases, it consumes draught and causes deposition of soot on the horizontal shelf. These eddies become more violent as the rate of air-flow increases, and at high velocities a considerable proportion of the ventilation



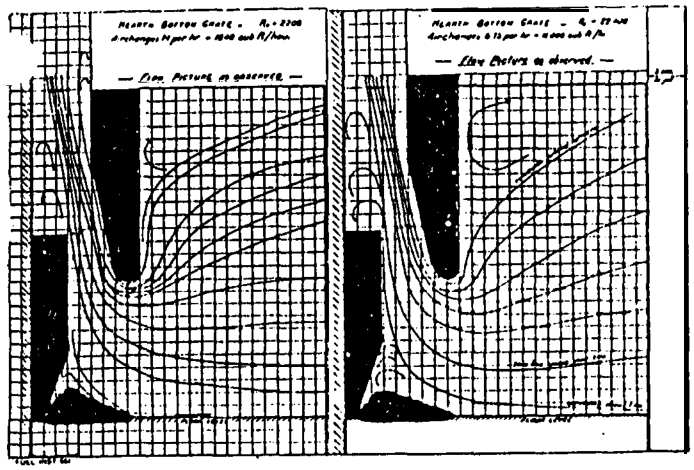


Fig. 20.

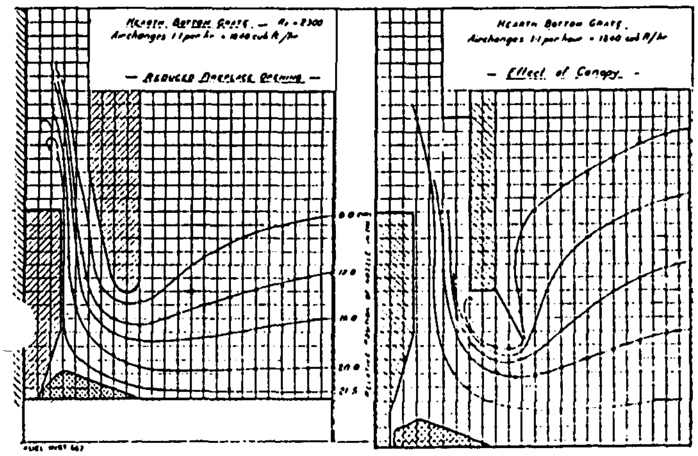


Fig. 22.

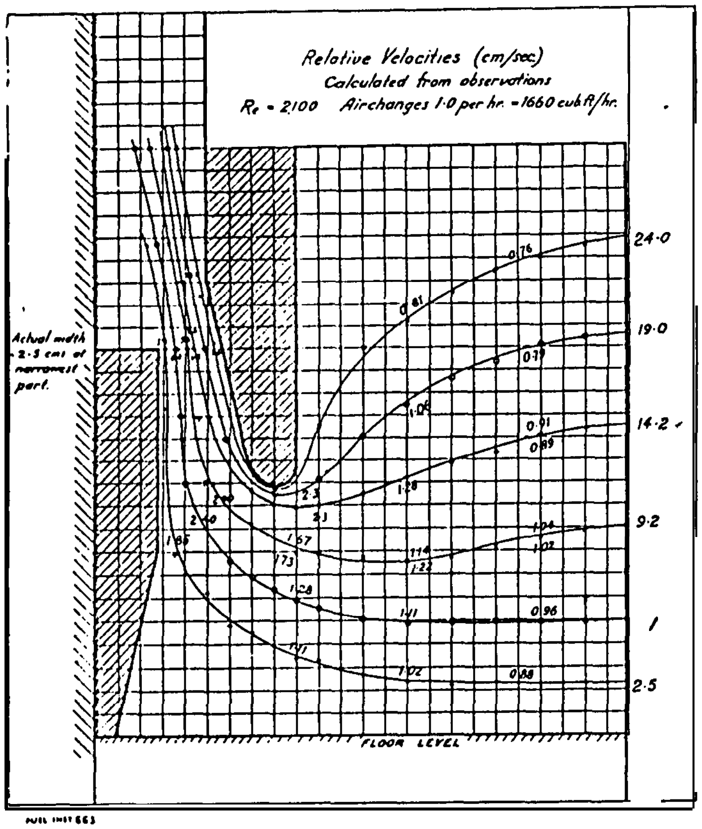
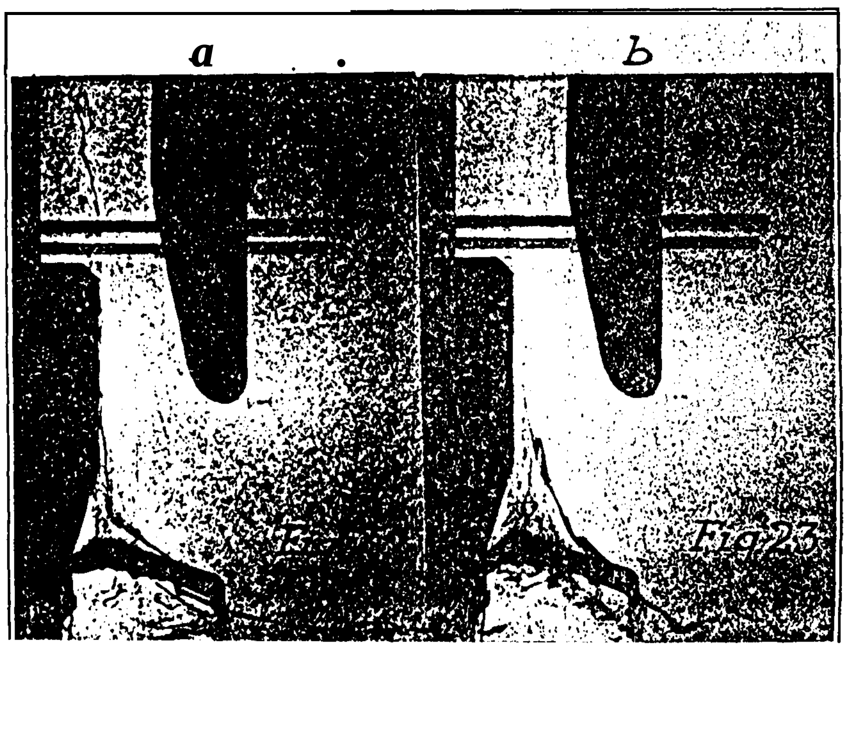


Fig. 21.

air joins and swells the eddying gases. The main part of the ventilating air, however, which enters the throat round the weir-shaped chimney-breast, streams, unaffected by the shelf-eddy, uniformly up the chimney in a stratified layer. It thus cools the wall of the chimney nearest the room, while the hot gases travel in eddies along the back wall, which is often an outer wall of the house. Even at high velocities the air-flow, unless it is disturbed by the chimney-breast itself, remains stratified along the front side of the chimney. In such cases the heat in the gases travelling up the rear wall of the chimney is largely wasted as regards warming the room. This can be verified by temperature measurements in chimneys by means of suitable gas pyrometers. The more pronounced the stratification the higher the gas temperature will be found near the back wall.

But before condemning the horizontal smoke-shelf causing the shelf-eddy, its other potential performances must be considered. There are many people concerned with fireplaces who believe that the smoke shelf, by forming a barrier against down-blowing winds, is necessary to prevent down-draught. According to them, the gas- and air-flow in a fireplace and its chimney takes place as shown in Fig. 24.(5) To decide this question it is necessary to go back into the history of the origin of smoke-shelves and smoke-chambers.

When Rumford started his practical experiments he was faced with very wide chimneys, in any case wide enough to allow the chimney-sweeps' boys to climb through. He rightly recognised—though without scientific reasoning—that the exaggerated width was the primary cause of smoky chimneys, although he attributed it only to the width of the throat and not of the whole chimney. The aerodynamic explanation is that in wide chimneys both the temperature and the velocity of the gas-air column are very low and not uniform. The pictures show, beyond doubt, that the gases cling to the back and do not spread over the whole chimney. An uneven distribution of temperature and velocity results, and it may easily happen that a division of the flow takes place.



A current of hot gases will stream up the rear side of the chimney while a current of cold air streams down the other side and enters the room mixed with smoke. This may arise especially if the access to the room of fresh air through other apertures like well-fitting doors or windows is less convenient than through a wide chimney. Rumford could, for many reasons, not cure this

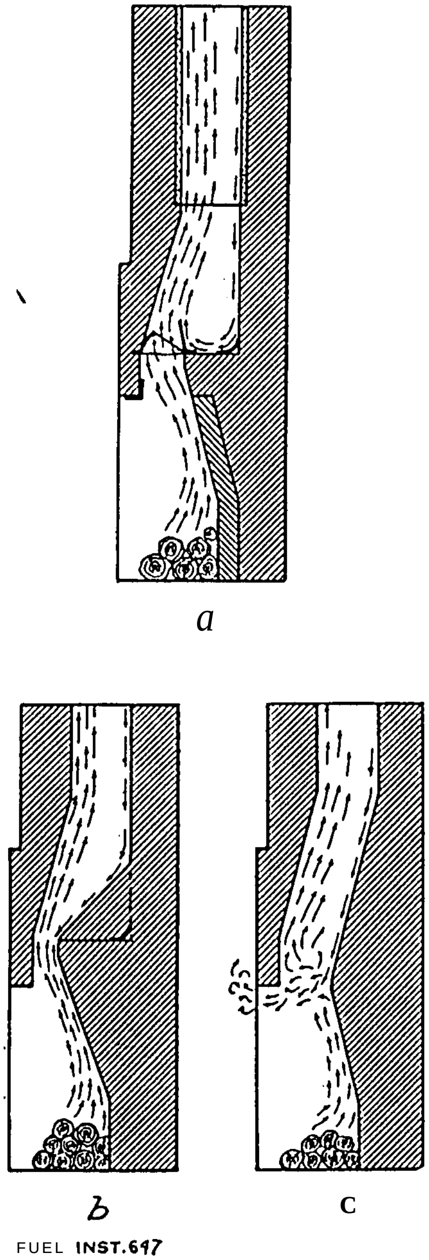
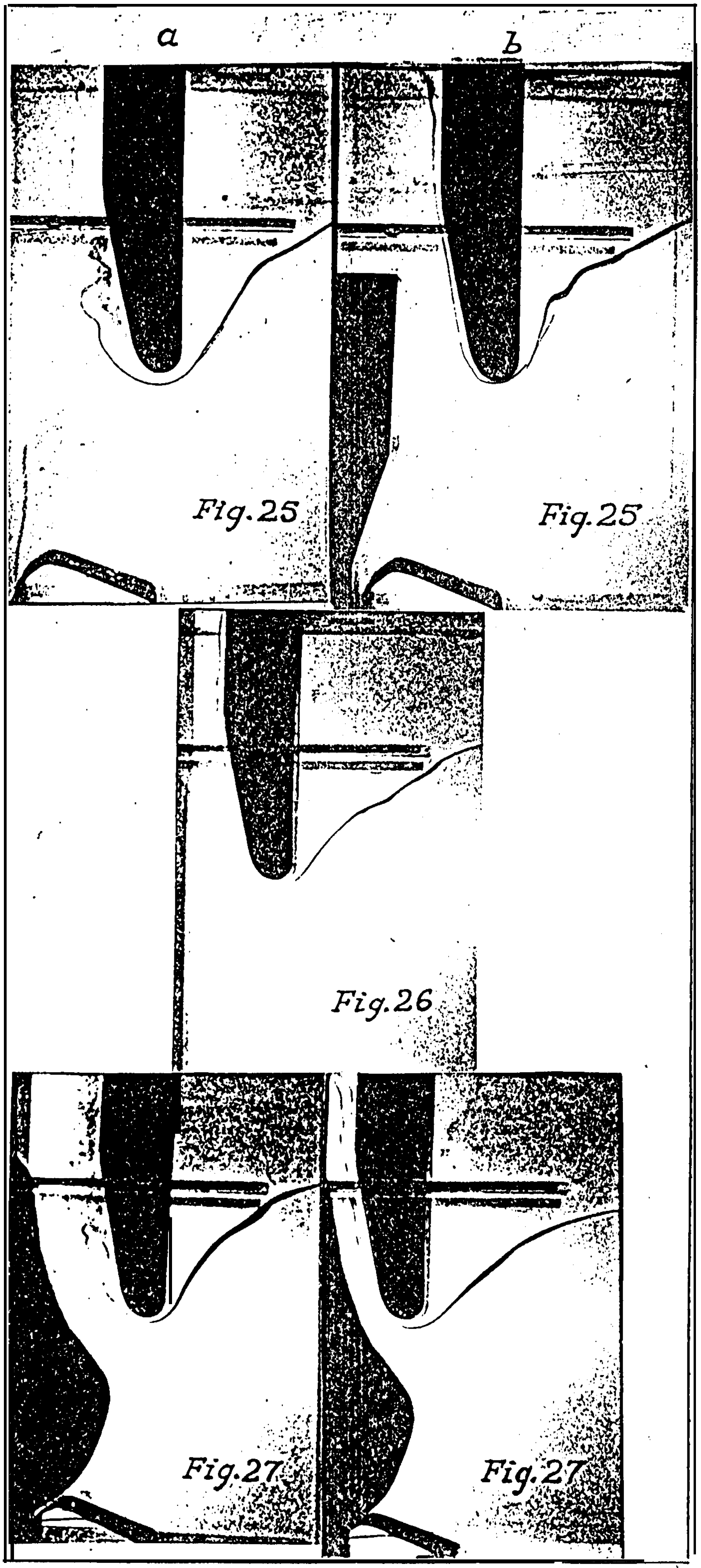
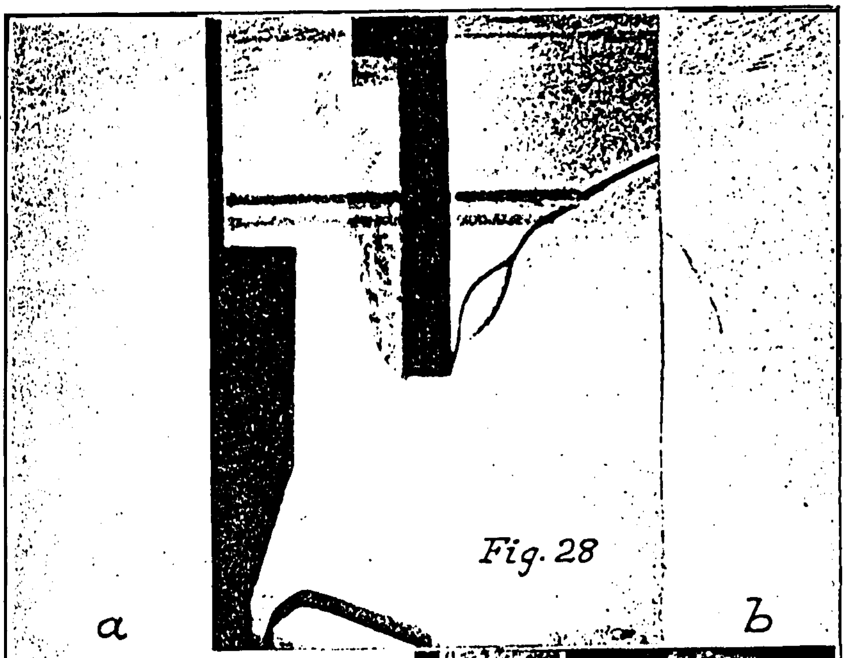


FIG. 24.

deficiency by narrowing the whole chimney, in the first place, because the necessary width for the sweeps' boys had to be upheld. Another reason which still holds good to-day is that the narrowing of the chimney in an existing house is an awkward and expensive matter. Rumford, therefore, solved this problem by introducing a secondary fireback which could easily be erected in the background of any fireplace. The fireback had to overlap





a Fig. 28 b

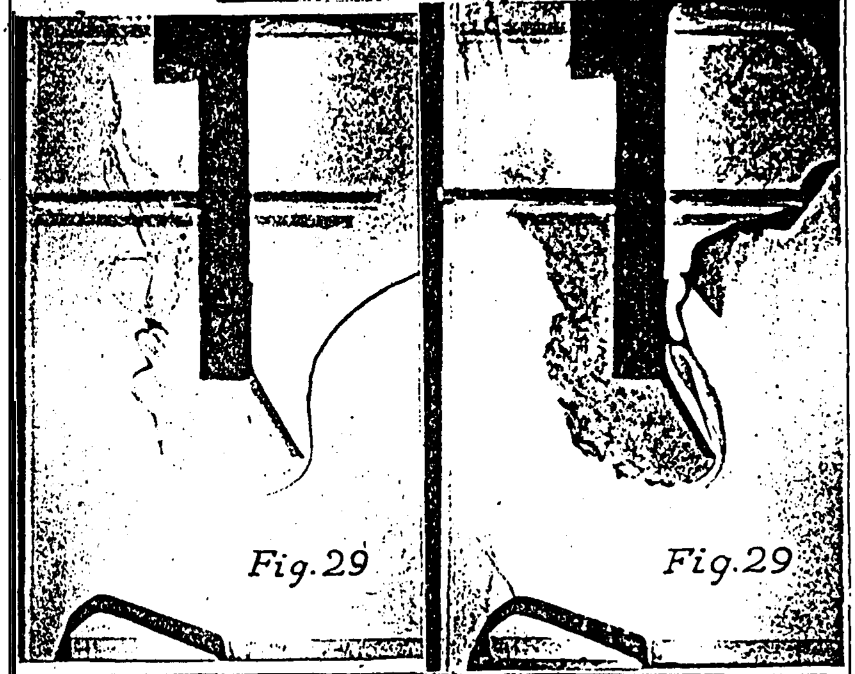


Fig. 29 Fig. 29

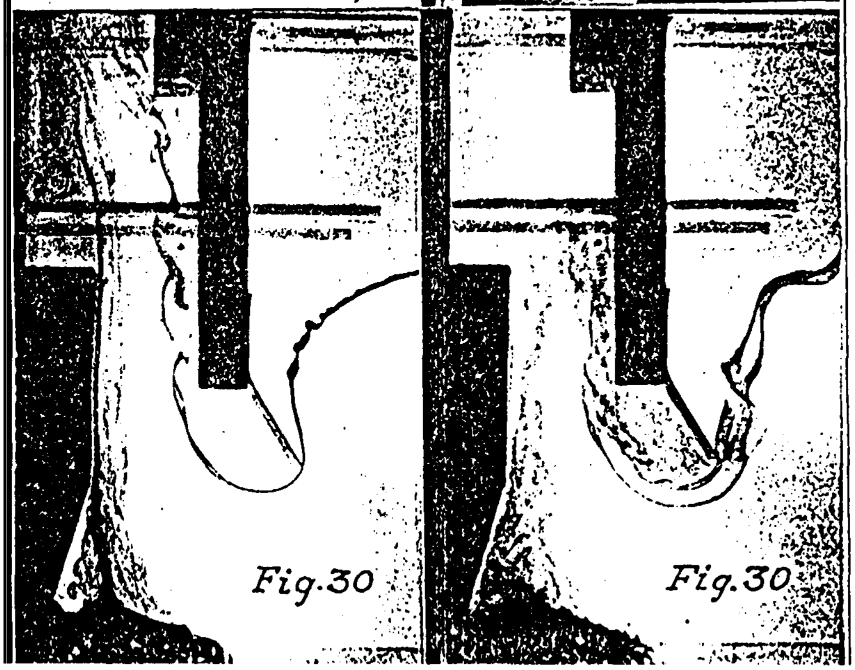


Fig. 30 Fig. 30

the lower edge of the chimney-breast, as shown in Fig. 7, and the width of the throat, recommended by Rumford, was 4 in. at the narrowest point.

The task of nevertheless permitting access into the chimney for the sweeping boys was solved by Rumford by making removable the two top bricks of the new fireback. It was easy to take them out before and to replace them after sweeping. Thus originated the smoke-shelf, to which Rumford was inclined partly to attribute his success, assuming that it formed a barrier against down-blowing currents. He therefore recommended a horizontal shelf instead of a trumpet-shape of the transition into the wider chimney. At this point Rumford's vision, admirable as it was, failed. He had no means to make perceptible the flow and did not realise that the hot gases rise closely clinging to the fireback and form an eddy

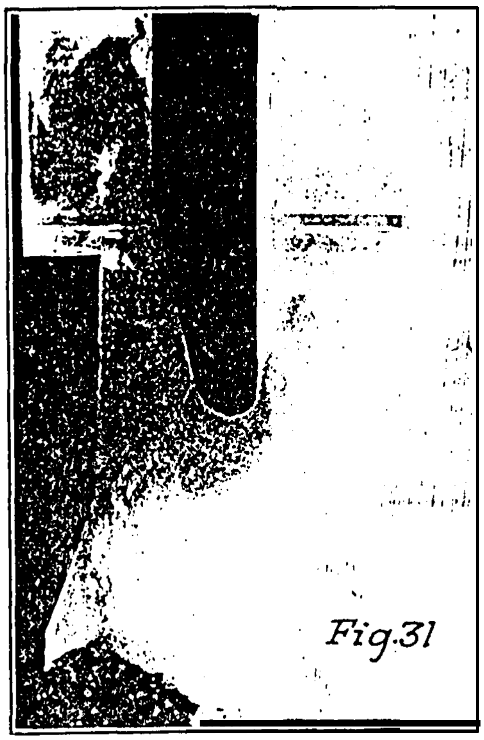


Fig. 31

above it, while the cold gases stream near the front wall. He adopted the opinion referred to in Fig. 24 and the triumphant success of his general design induced the belief that all features in it were indispensable. When, later, sweeping chimneys by climbing boys was abolished and narrower chimneys became possible, the erroneous conception of the effect of a smoke-shelf kept it alive and led to the birth of a smoke-chamber.

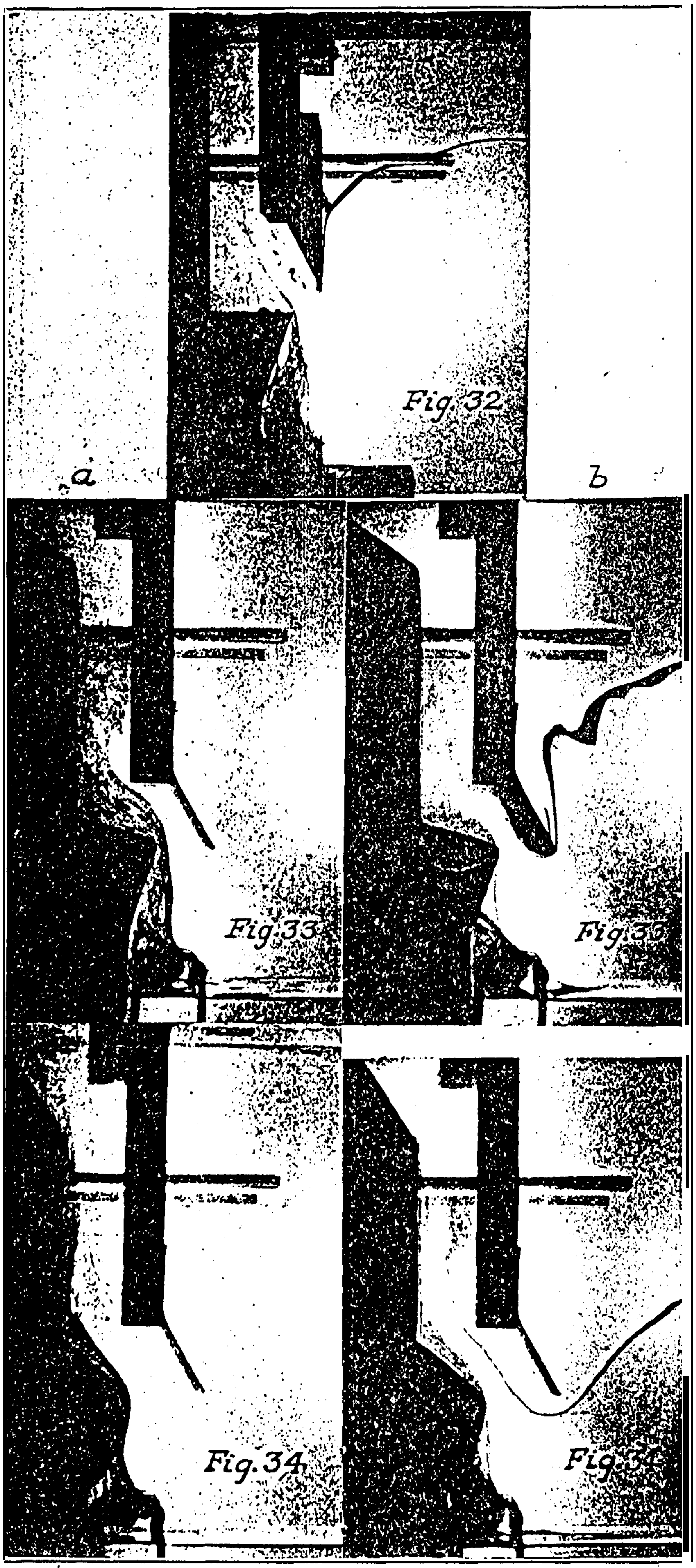
In reality, the success attained by Rumford is accomplished by the increased velocity in the throat, which can be checked quantitatively in Fig. 21. The higher energy and more uniform velocity of the stream in the throat makes it much more difficult for any counter-current to pass downwards through this upwards-directed rapid. That this recognition is correct will be proved in the following paragraph.

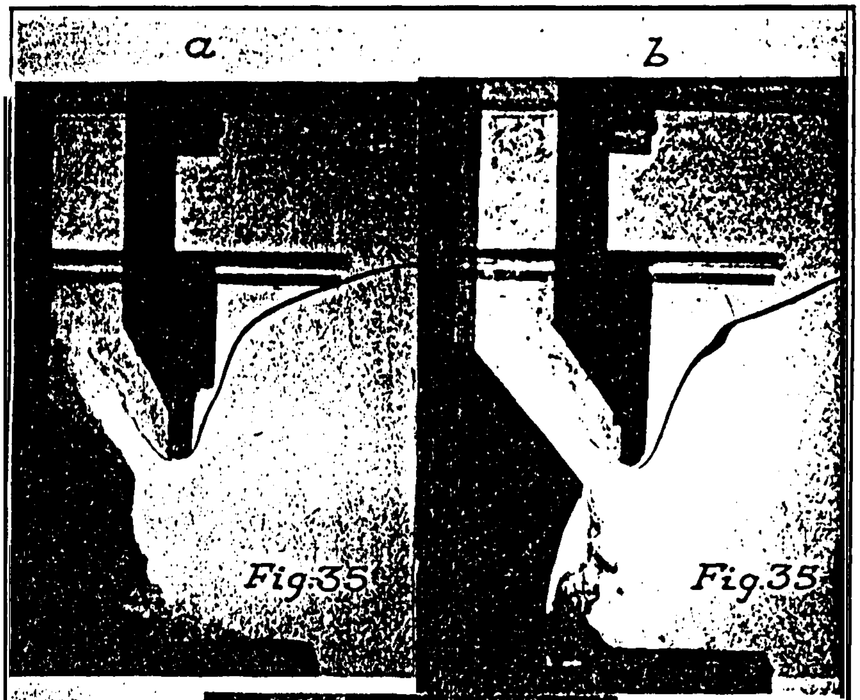
C. The Chimney-breast and Canopy Eddy.

The deciding experiment was to study the nature of the flow in a wide throat without a Rumford fireback and to investigate whether a full explanation for the untloubtcd success of the fireback could be founcl. Such a test was, at the same time, an *experimentum crucis* for the model, for-since this was a truly aerodynamic problem-a true similar model was bound to respond to it. The salt solution representing the combustion gas clung in csactly the same manner to the back wall and streamed up the chimney without any disturbance. But the introduction of a flow line revealed at once that behind the chimney-breast a dangerous eddy was formed, which is photographed in Fig. 25*a*, but disappears as soon as the fireback is introduced in Fig. *256.* This shows that, even with a weir-shaped chimney-breast, too wide a throat produces an eddy in which the air, mixed with combustion gases, streams back and tends to re-escape into the room. This type of breaking-away eddy is well known to those concerned with aerodynamic processes.

That the disappearance of the chimney-breast eddy by introduction of the fireback is entirely due to the increased velocity and not to a peculiar property of the fireback or smoke-shelf is proved by Fig. 26. Here the eddy has been made to disappear equally well simply by advancing the chimney-breast towards the rear wall. The same is shown in Figs. *27a* and *27b*, where narrowing the throat and chimney extirpates the eddy behind the chimney-breast.

The discovery of an eddy even behind a smoothly curved Rumford weir led to the investigation of less favourably shaped chimney-breasts and canopies. Fig. 28 shows that a chimney-breast with sharp corners causes a violent eddy even in a throat, the width of which is reduced by a fireback. If such an angular chimney - breast is further equipped with a sharp-edged canopy the eddy becomes catastrophic, as shown in Figs. 29*a* and *290.* Here the narrowing of the throat by the correct introduction of a Rumford fireback as shown in Figs. 30*a* and 30*b* somewhat reduces the extension of the eddy in the throat, but is unable to prevent it and does not at all affect the eddy behind the canopy. Especially Fig. 30*a* shows the two eddy-fields, the one above the horizontal smoke-shelf, the other behind the canopy and the front wall. It is quite clcir that from the shelf-eddy no smoke can directly escape into the room. It is in the canopy and chimney-breast eddy that a current of air and gas travels down all along the inner side of the front wall, opposite to the direction of the main flow. This is the pacemaker for down-blowing winds. Any squall inter-





a b

Fig. 35

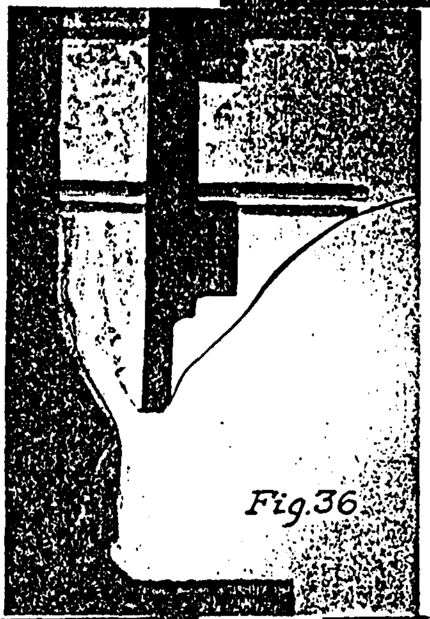


Fig. 36

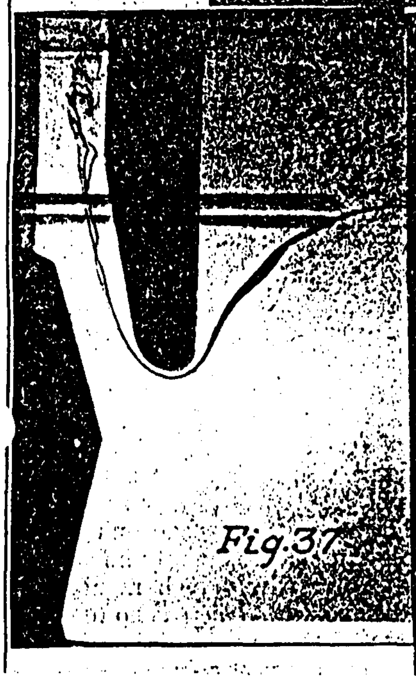


Fig. 37

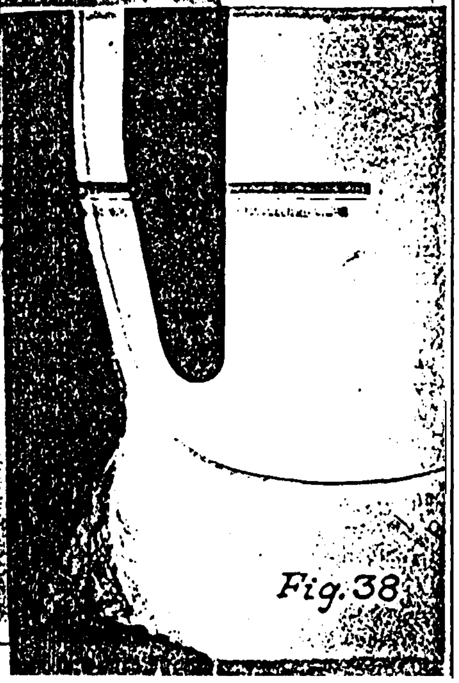


Fig. 38

rupting the uniform discharge out of the chimney is likely to push into the room the puff of smoke lurking behind the canopy and breast.

It could be well observed in the model that when the flow was restricted the combustion gases streamed up close to the back wall and were met by a counter-current flowing down along the front wall, as indicated in Fig. 31, which seeks to reproduce a badly smoking fireplace.

D. *Testing the Flow in any Design of Fireplace.*

By means of the model it is possible to determine quickly the aerodynamic features of a fireplace of any construction, to trace defects and to find the most suitable aerodynamic shape. All that is necessary is to make small wooden *or* sheet metal models of the respective fireback, chimney-breast with canopy, throat and smoke-chamber, and fit them in a similar position into the model.

The main feature found in fireplaces of the present day is the co-existence of the two eddy-fields, the shelf eddy and the canopy and chimney-breast eddy. Possible causes of interacting eddies of combustion gas and ventilation air are :—

Projecting bullnoses or apices with receding shelves.

Too wide a throat.

Narrow throats opening too abruptly into a smoke-chamber or chimney.

Angular chimney-breasts.

Sharp-edged canopies.

Sudden changes of direction.

Dead spaces.

Uneven inside lining.

The photographs herewith give a few examples out of a greater number of commercial fireplaces tested in the model.

Fig. 32 shows a design with a very pronounced apex in a low position, an exceedingly large horizontal smoke shelf, a throat opening suddenly into a smoke chamber, and an angular chimney-breast with a sharp canopy. There are two violent eddies interacting with each other. A counter-current flows downwards inside the front wall behind the canopy. In point of fact, the actual chimney emits puffs of smoke round the canopy into the room as soon as the atmospheric conditions are dull or a blast of wind hits the cowl.

Fig. 33 (a) and (b) shows a construction with large, nearly horizontal shelf, the apex being, however, sheltered by the canopy. There is no smoke chamber, but an angular chimney-breast with sharp canopy and two abrupt changes of direction in the chimney. Fig. *33a* shows a fine example of a shelf-eddy, extending upwards in the chimney and striking the front wall. Fig. 33*b* demonstrates the canopy eddy combining in the chimney with the shelf-eddy.

Fig. 34*a* shows a sloped shelf leading into.

sharp canopy, the angular chimney-breast, and the abrupt changes of direction are like those in the previous picture. In this picture, however, owing to the sloping shelf, the shelf-eddy is much reduced. The picture is a good example of how the gases, in spite of a pronounced apex, cling to the back wall. Fig. 34*b* shows that the ventilation air entering the chimney at some distance from the canopy is not entangled in the canopy eddy as compared with Fig. 33*b*, but having passed the sharp corner of the chimney-breast, forms an eddy, which causes a down-stream along the inner breast wall.

Fig. 35 (a and 6) shows plainly how, by a sloping shelf, the shelf-eddy can be reduced. There is, however, a dangerous chimney-breast eddy left, mainly due to the vertical recess of the chimney-breast.

In Fig. 36 the shelf-eddy is entirely avoided, but the angular chimney-breast and the abrupt opening into a wider chimney of the narrow throat creates an eddy which countenances the emission of smoke puffs into the room.

E. *The Prevention of Eddies.*

The eddies observed in throats and chimneys belong to the aerodynamic category of " breaking-away " eddies, and the resistance to flow caused by them is registered under the group of phenomena known as shape resistance. This resistance is produced by the tearing off of the flow behind a body.

The canopy eddy is due to the fact that a streamline cannot turn round an angle of 90". For this would mean a motion with an inlinitcly small curve radius resulting in inlinitcly great centrifugal forces. To avoid breaking-away eddies, it is necessary that the streamline boundary to the body should not undergo a greater change of direction than IO" to 12".

Only by the very gradual enlargement of cross-sections and the complete absence of sharp edges, therefore, can breaking-away eddies be avoided and the cross-section filled by a uniformly directed How.

Breaking-away eddies always occur if the solid surface along which the flow streams ends abruptly or changes its course too suddenly. Whilst cddics are often desired and artificially produced in order to intensify the velocity of combustion, in all transport phenomena they arc always detrimental and increase the resistance, whether one has to deal with the wings of aeroplanes, with trains and motor-cars, or with chimneys. In the case of the open fire they are particularly disagreeable because the available chimney-draught is often enough on the verge of in-sufficiency and the esistcnce of cddics may lead, at the slightest disturbance by the wind, to puffs of smoke into the room. In this respect the shelf-eddy is much less dangerous than the chimney-breast eddy, which favours downward currents and countenances the emission of smoke. As Rumford has shown and the cspcricncc of the Building Research Station has proved, the narrowing of too wide a chimney-throat by a lircback is so cffcctivc that the creation of a shelf-eddy is inferior to the elimination of the chimney-breast eddies which arc inevitable with too wide chimneys.

The previous pictures have already shown the way leading to the total avoidance of eddies. Smoke chambers and shelves must be regarded as survivals of a past age. The model tests have shown that the liability to downward currents is far greater close to the front wall, where the canopy eddy facilitates them. The shelf or any other sudden transition in the rear wall from a narrow throat into a wider smoke chamber or chimney is unable to stop this downward current at the opposite side. What cannot be accomplished by the higher velocity in the throat cannot be amended by a shelf, which only creates smoke eddies.

Fig. 37 shows that even with a steeply sloping fireback and a weir-shaped chimney-breast the front eddy is not entirely avoided if sudden corners, however small, are left.

Fig. 38 finally shows a streamline chimney without a canopy, shelf or smoke chamber, in which no eddies are present. But this can only be accomplished, if the chimney is not much wider than the throat, and the lateral contraction very gradually effected. The three fundamental requirements are therefore

(1) A weir-shaped chimney-breast without a canopy.

(2) A narrow chimney.

(3) No discontinuous contractions and no expansion-angles greater than 12".

Simple though a construction like Fig. 38 appears, it contradicts many of the present-day designs as much as a streamline locomotive differs from an ordinary one. And before all, it is at variance with the csisting building by-laws. A conscientious consideration of all items and consequences becomes, t hcrcfore, indispensable.

The only thing that can be said in favour of throat eddies is that they break up the stratification in the chimney. Otherwise, they consume draught, cause soot deposits on the shelf and result in unstable conditions of flow. But stratification is more pronounced and longer maintained in wide chimneys, and smoke-shelves and chambers were resources to overcome the defects of too wide chimneys. Aerodynamically, there is no need either for shelf or chamber, nor are, for normal open fires, flues wider than 20 to 30 sq. in. required. The London County Council's Building By-laws (6) prescribe for open fires that no flue shall be less than 7½ in. across in any direction. This means l-hat the minimum cross-section of circular flues must not be less than 44 sq. in., and of square flues not less than 56 sq. in. The objections which could be rniscd against too narrow chimneys are :-

(l) That their resistance might be so high as to prevent them from carrying off the distillation and combustion gases.

(2) That the draught might be too low to keep the fire burning.

(3) That the ventilation of the room might be insufficient.

(4) That a narrower chimney might prematurely become choked with soot and tar deposits, or at least require more frequent sweeping, if highly bituminous coals arc used.

(ad.1). There is no doubt that a 20 sq. in. chimney can easily take up and convey the combustion gases of an open lire. The pictures have already clearly enough shown that the combustion gases, if left alone, cling to the back wall and only require a small fraction of the cross-section of wide chimneys.

(ad. 2). The flow pictures have already manifested, what will be proved quantitatively in Chapter V, that the rate of burning in a normal hearth bottom-grate is entirely independent of the draught. In these grates the fire burns as if no chimney csisted. It will further be shown, that, with the normal height of fireplace opening, also the combustion on a stool-gmtc is considerably influenced by the draught only at an excessively high number of air-changes which should be avoided. There is 110 foundation for the fear, therefore, that the rate of burning in open fireplaces would suffer by narrower chimneys.

(ad. 3). This point requires the most careful consideration. The **London** County Council's By-laws prescribe (7) t the ventilation of a room must not be less per hour than 750 cu. ft. of air per occupant or per 50 sq. ft. of floor area, whichever requires the greater ventilation. The room to which the model experiments refer has a floor area of 193 sq. ft. and requires, therefore, a minimum of 2,900 cu. ft. or 82 cu. In. *per* hour of ventilation air. Table I shows that this is satisfied by two air-changes per hour of the room under consideration.

The amount of ventilation air is dependent on the suction capacity of the chimney. This is a function of the chimney-height and the mean temperature of the rising gas-air column in the chimney, but reduced by the resistance due to friction and eddies. The gas temperature in a narrow chimney is, at a given heat input, certainly not lower, but probably higher, because the heat conducting surface is smaller. The resistance is reduced by the removal of eddies, which otherwise are almost inevitable in the transition of a narrow throat into a wide chimney. The wall friction, no doubt, increases with decreasing diameter. But the pull of a chimney does not increase proportionally to the increasing diameter. Practical tests have shown that only in the range of a very small cross-section the increase of capacity is almost proportional to that of the cross-section, whilst from about 20 sq. in. upwards, the increase considerably slows down and, from about 30 sq. in., ceases to justify the cost and space required by a further enlargement. This holds in particular, if the pull of wide chimneys is frustrated by narrow throats of an eddy-forming design. Moreover, the ventilation is more frequently checked by inadequate ...ess apertures. Even if the gaps of doors and windows total the same cross-section as a chimney, the resistance to the influx of air through such narrow clefts is much greater than that of a chimney.

As far as calculations can be relied upon, chimneys of 20 to 30 sq. in. have no difficulty in producing the ventilation required by the by-laws. The avoidance of too high a number of air-changes is but to the advantage of the true efficacy of an open fire. The air sweeping by excessive ventilation of rooms makes the heating by open fireplaces rather illusory. No sooner are the objects in a room warmed by radiated heat from the fire than the excess air cools them, carrying back into the chimney the heat just emitted.

(ad. 4.) The deposition of soot and tar at the chimney walls is more likely to decrease. Soot, understood as fine solid particles suspended in the gas, is preferentially separated by eddies, low velocities and dead spaces. Hence, the better filling of a narrow chimney by the gases at higher velocity and the absence of eddies will help to avoid soot deposits. Tar crusts are the result of a condensation at lower temperature. Since the chimney temperature is always lower than the condensation temperature of the heavy hydrocarbons, evolved after each refuelling of bituminous coal, tar deposits in a chimney are unavoidable with these coals. The higher, however, the chimney temperature and the velocity, the less incrustations take place. Continental experience with narrow smoke pipes behind stoves burning coals of a high tar content shows that no trouble is caused by premature choking. It may, however, be argued, that smoke chambers with shelves serve as soot catchers, retaining smoke that otherwise would pollute the atmosphere. Even if this were the case, such a method of smoke abatement is certainly not to be recommended, for the accumulation of soot and pitchlike hydrocarbons in domestic flues is both unhealthy and dangerous. But the constructions recommended on the strength of the model tests will also prevent the ventilation air from chilling the fireback and the combustion gases, and consequently reduce the actual formation of soot and the incomplete combustion of the tarry matter.

The temperature distribution in narrow chimneys would be more uniform, since by the natural turbulence of the flow the heat transmission across a smaller area would be more quickly attained.

No deterioration either of combustion or ventilation can, therefore, be seen following the adoption of 20- to 30-sq. in. chimneys. Combined with a shelfless throat and correctly designed chimney-breast, narrow chimneys of stream-line construction in which all eddies are eliminated would not only cure many defects, but also reduce the space required for them in a building. In consequence, either the cost would also be reduced or the rent-earning space increased.

This implies, however, an alteration of the existing by-laws, and before this is advocated the practical tests, now in progress, which have so far confirmed the model results, must be continued over a still longer period.

F. *The Functions of the Fireback.*

The flow problems of the open fire are not completely solved by attention to the chimney design alone. The shape and the position of the fireback profoundly influence the performance of the fire. They control the flow of the combustion gases immediately above the fire, and they determine whether chilling ventilation air strikes the fireback or not. Shape, position and arrangement of the fireback also govern the reflection of heat back *on* to the fire and the vertical distribution of heat radiation into the room. A maximum of well-distributed heat emission into the *room* must be combined with the most favourable aerodynamic features. It follows that only a minimum of cold air should meet the hot gases and strike the radiating fireback. This is a most important requirement, but one which is not easy to fulfil. It has not been possible so far to measure separately the radiation emitted by the solid incandescent fuel, by the flame and by the fireback. Consequently, the part played by each of these factors is unknown and it can, of course, not be studied in a model.

The heating of the fireback is assisted by the tendency of the hot gases to cling to it and this must not be interfered with by the ventilation air. Cold air reaching the fireback cools it by convection and, at the same time, hampers the ignition and combustion of the volatile heavy hydrocarbons. This leads to the formation of smoke and the deposition of soot and tar.

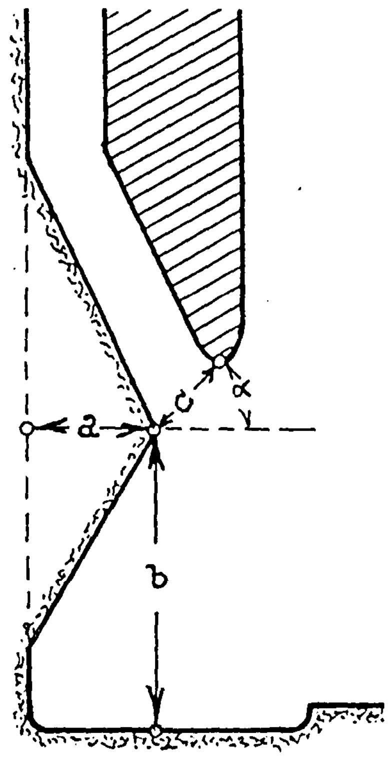
There is no doubt that the action of a hot fireback can greatly improve the efficiency of a fire and reduce the emission of smoke into the atmosphere. But it would be quite erroneous to expect that by aerodynamic improvements alone the discharge into the atmosphere of smoke from open fires burning bituminous coals could be overcome. The production of smoke is a problem of ignition of the fresh and refuelled coal, and of combustion of the evolved distillation gases. It is therefore primarily a thermal and only in the second place an aerodynamic problem.

Every measure should therefore be taken in order to make and keep the fireback as hot as possible. Such measures are : The fireback must be exposed to the radiation of the coal-bed ; it must be fully swept by the flame or hot combustion gases ; it must not be touched by cold air ; it should be well insulated against conduction heat losses.

There are four geometrical magnitudes determining the performance of a fireback. These are shown in Fig. 39.

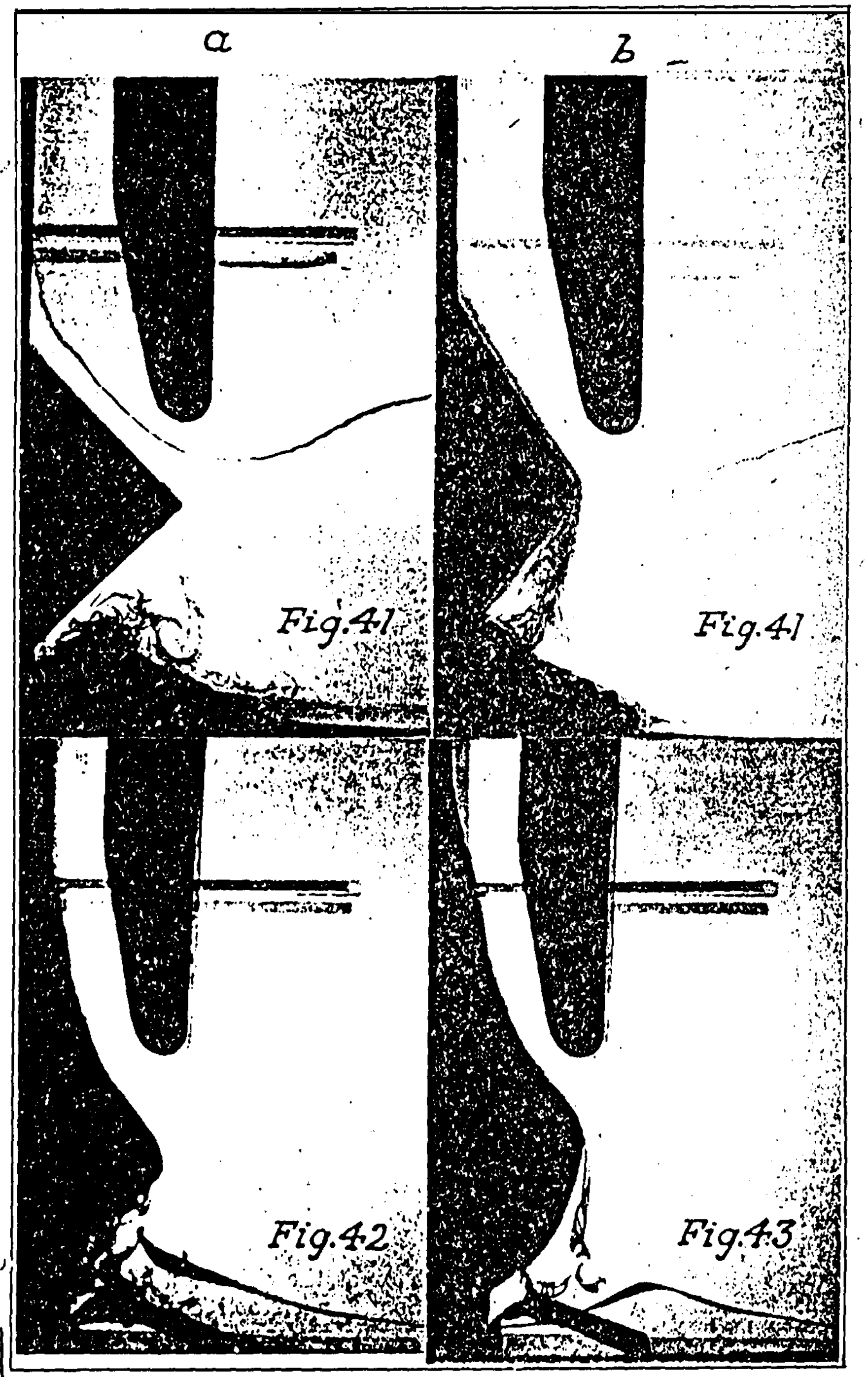
(1) The degree of pronouncement-that is, the horizontal distance *a* between the apex and the deepest recess of the grate.

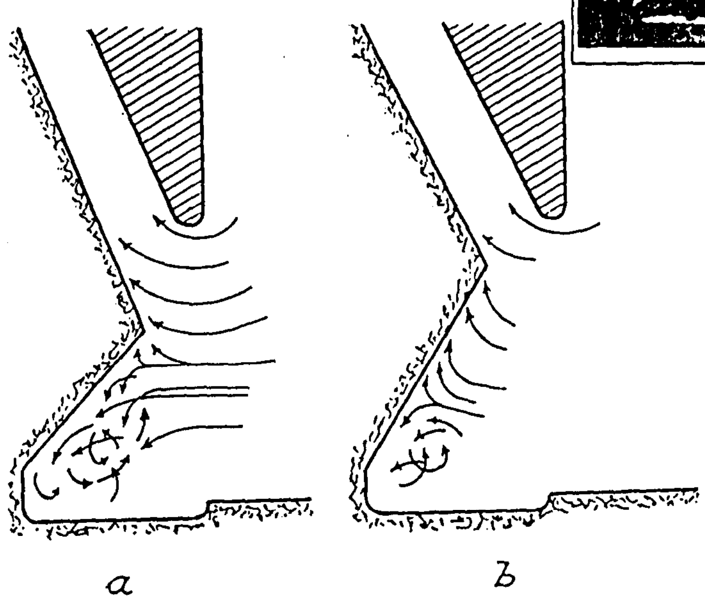
(2) The height *b* of the apex above the grate, which together with a determines the degree of sloping.



FUEL INST.659
FIG. 39.

(3) and (4). The distance c between the apex and the tip of the chimney-breast and the angle a which the connecting line forms with the horizontal. This angle is positive if the chimney -breast ends above, and negative if it extends below the apex.





FUEL INST.646
FIG. 40.

A pronounced triangular apex intercepts the lower stream of ventilating air, and this happens the more, the lower the position of the bullnose and the more, therefore, the fire is sheltered underneath the slope as in Fig. 40*a*. The floor air is then driven down to the fire creating an eddy which chills the combustion and distillation gases and seriously disturbs the flame, as shown in the exaggerated case of Fig. 41*a*. With an equally pronounced but higher situated apex, as in Fig. 406, the slope is steeper and the floor air less intercepted. But in turning upwards the cold air strikes and chills too much of the fireback. Fig. 41*a* and *b* show in general how much the character of the gas flow underneath a fireback is influenced by its position and shape.

With straight sloping backs it seems that neither the interception of floor air nor the contact with the knee-level air can be avoided, and curved firebacks were therefore tried in the model. A concave fireback, as shown in Fig. 42, intensifies the eddy of the intercepted air. Fireback cddics of this kind can be so violent as to throw smoke from the fire right out into the room. The concave back also has the disadvantage of reflecting too much down to the fire and on the floor of the room.

A convex fircback, shown in Fig. 43, is much better, both for air-flow and heat distribution. Less air is intercepted by the apex and the fircback eddy is greatly reduced. The fireback and gases are not prematurely chilled and heat is uniformly reflected and racliatccl clown to the fire and into the room. These examples show that an exaggerated slope resulting from a low pronounced bullnose is disadvantageous. Neither for aerodynamic nor thermal reasons is an apex required protruding more than half of the depth of the fireplace. But the curvature of the back should bc such that, respecting both flow and radiation, the best effect be attained. This appears to be the case with the convex back because in its lower

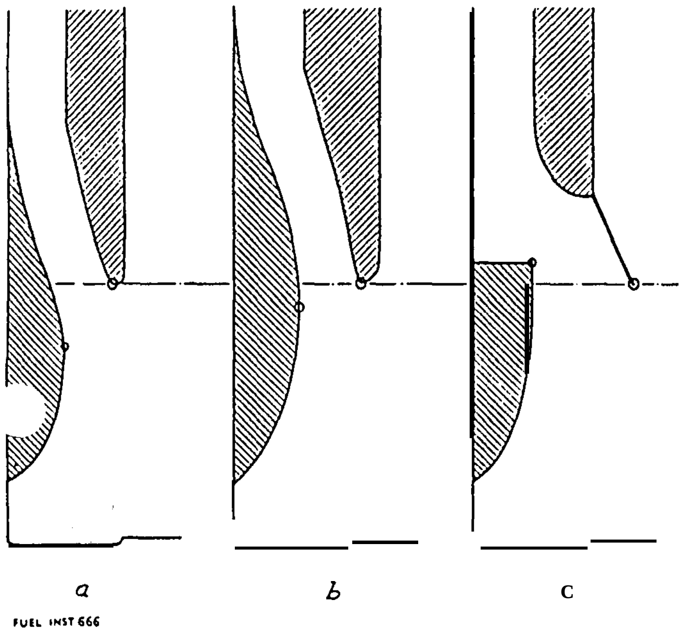


FIG. 44.

part it reflects the heat down to the fire and the floor, whilst in its upper it distributes the radiation well into the room.

The last question to solve is the position of the chimney-breast tip in relation to the apex. If the fullest benefit of the spncc-saving reduction of the chimney width is to be realised, the chimney-breast must end above the apex as shown, for example. in Fig. 38 or 43. As Fig. 44 points out, any raising of the apex relatively to the fixed height of the breast would either advance the *front wall into the room, or neccssitntc the application of a thin, sharp-edged canopy and a horizontal smoke shelf.

G. *Film.*

Of all flows and occurrences described in this chapter, a 16-mm. film was taken by Captain B. Brandt, which, together with its captions, is 800 ft. long and lasts half an r. Here the model showed its greatest advantage by ing possible a film of all details of the otherwise invisible motions of air and gas in open fireplaces, their throats and chimneys. The film is the property of the British Coal Utilisntion Research Association,(@) to whom inquiries should be directed.

This film was first shown bv the author to an audience of architects, builders, coal -producers and clistributors, and coal-burning appliance manufacturers and merchants at the Institution of Civil Engineers, on December 1, 1938.

V. The Rate of Combustion as Dependent upon the Aerodynamic Conditions.

A. *The Reaction-Velocity Criterion.*

In Chapter IIA it was explained that the velocity with which the solution of a salt body proceeds perpendicular to the dissolving surface is a measure of the reaction velocity and can be csprcsscd as $\frac{\text{cm}}{\text{sec.}}$. The same conception holds for combustion. In all surface reactions between a **solid** and a liquid phase, this reaction velocity depends on the flow velocity with which the liquid phase streams past and round the solid body. The reaction velocity increases with increasing flow vclocitp, but mostly at a different rate. The ratio $\frac{c}{v}$ between the reaction velocity c and the flow velocity v becomes, therefore, the most important criterion if the relations between reactivity and flow arc to be investigated.

The direct determination of c might be effected in the case of a dissolving salt, but is impossible with burning coal. But if d clcnotcs the thickness or diameter or any other dimension of length in centimctrcs perpendicular to a reacting surface, and t the time in seconds during which the reaction cstcncls over this length d,

$$c = \frac{d}{t}\left[\frac{\text{cm}}{\text{sec}}\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

It is not altogether easy to establish true values of d for particles of irregular shape. But d is proportional to the volume/surface ratio $\frac{V_p}{S_p}$ of a particle. If W is the particle weight and γ_L its lump density, then—

$$c = \frac{d}{t} = \frac{V_p}{S_p \times t} = \frac{W}{S_p \times \gamma_L \times t}\left[\frac{\text{cm}}{\text{sec.}}\right] \quad . \quad . \quad (29)$$

whence it can be more easily determined.(9) It follows that

$$\frac{c}{v} = \frac{V_p}{S_p \times t \times v} = \frac{d}{t \, . \, v} \quad . \quad . \quad . \quad . \quad (30)$$

This is the dimensionless criterion characterising the turn-over of substance as dependent on the flow conditions and particle size. For combustion, t is the combustion time and v the velocity of the combustion air, preferably measured below the grate.

If frill similarity is to csist between two processes in which a solid body reacts with a streaming liquid corresponding values of $\frac{d}{t \, . \, v}$ must be equal. This means that at any two corresponding points the ratio between the increase δv of the flow velocity and δc of the reaction velocity should be identical—

$$\frac{\delta c_1}{\delta v_1} = \frac{\delta c_2}{\delta v_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

With a solution process the accelcrntion of dissolution is entirely caused by hydrodynamic reasons ; with combustion, however, any acrodynamic nccclerntion of the combustion is accompanied by a rise of temperature which, for its part, also accelerates the reaction velocity. The total accclcrntion of solution, following an increase of flow velocity, is therefore due to streaming reasons alone; whilst the total acceleration of combustion is partly ncrodynnmic, partly thermal. For combustion, the relation holds

$$c = f\ (v,\ T) \quad . \quad . \quad . \quad . \quad . \quad (32)$$

T being the temperature of the fuel bed. Consequently, also in this respect, only partial similarity exists between solution and combustion. But it also follows that the aerodynamic component of the acceleration of combustion can well be compared with and studied by the acceleration which the solution of a salt body or bed undergoes under the effect of increased flow velocity. The comparison rests, therefore, on the assumption of two isothermal processes. The greater the rôle played in combustion by the thermal component, the more will the results obtained by solution fall behind the values which must be expected for combustion.

If proper use is made of this fact, it is no inadequacy of the method but an advantage. For it was intended to isolate and bring home by the solution tests the cffcct of the aerodynamic element. Hitherto it was impossible to distinguish between the aerodynamic and thermal acceleration. Now, once the first has been established by the solution experiments, the thermal acceleration may be found as the difference between the total and aerodynamic acceleration. This would be a very valuable contribution to our knowledge of combustion and fuel.

Bythesolutionexperiments described in Appendix II, the time required to dissolve a certain weight of salt was determined. Since the lump density and surface of the particles forming the salt bed were exactly known, it was easy to calculate the reaction velocity—

$$c = \frac{W}{S_p \cdot \gamma_L \cdot t} = \frac{d}{t}\left[\frac{cm}{sec}\right] \quad . \quad . \quad . \quad (33)$$

for diffeien't sizes.

B. *The Results of the Solution Experiments.*

The objective of the solution cspcrimcnts was to establish quantitative relations between the rate of burning in a fireplace and the chimney draught. · That such relations existed was known qualitatively.

" Already Rumford ([10]) had observed that the draught and the rate at which the fuel burns both depend upon the distance between the top of a fire and the entrance to the flue throat. If this distance is too great, much of the air enters ttrc flue directly without having first come into contact with the burning fuel. As a consequence the draught (on the fire) and the rate of combustion are diminished. On the other hand, if the distance is so small that practically the whole of the air is forced over or through the fuel the rate of combustion may become excessive."

Dr. Fishenden ([3]) has made a series of cspcrimcnts to study the effect of draught restriction upon the heat absorbed by the air passing up the chimney. She found : " When resistance to the flow was introduced by pushing in the damper the rate of burning of the coal was reduced, though relatively in a smaller proportion than the air flow. But when resistance to the air flow was introduced by diminishing the aperture in the ash-guard beneath the grate the rate of burning of the fuel for the same reduction in draught was cut clown much more rapidly."

A still more detailed investigation of this problem has been carried out by Hales,([11]) who comes to the conclusion : " The draught will depend on a number of factors such as the construction and height of the chimney and atmospheric conditions, and its effect on the fire will further be dependent on the distance between the chimney throat and the fuel level, on the type of grate, and on the size of fuel."

All the authors quoted agree, therefore, that a relation exists between what is called draught and the rate of combustion, but no quantitative expression for these relations could be established hitherto, and the aerodynamic investigation of this characteristic flow problem was still missing.

The solution experiments were carried through with different flow Velocities, corresponding to a range from still air up to eight air-changes per hour, with different distances between the salt bed and the chimney-breast, and with different particle six. In addition the width of the throat was variccl. For the evaluation of the results the intensity of flow is best expressed by the Reynolds Number in the throat according to Fig. 8. The distance *H* between the floor and the tip of the chimney-breast must be related to another characteristic length of the fireplace which alone makes it possible to transfer the rcsutts to a full scale fireplace. The best magnitude of reference is the hydraulic mean depth *D* of the throat (see III, B.).

The experiments with various heights of openings were always started with no flow at all, the salt dissolving with its natural Velocity in still water. In this case the reaction velocity c_0 is only dependent on the velocity with which the heavier solution sinks down. The degree

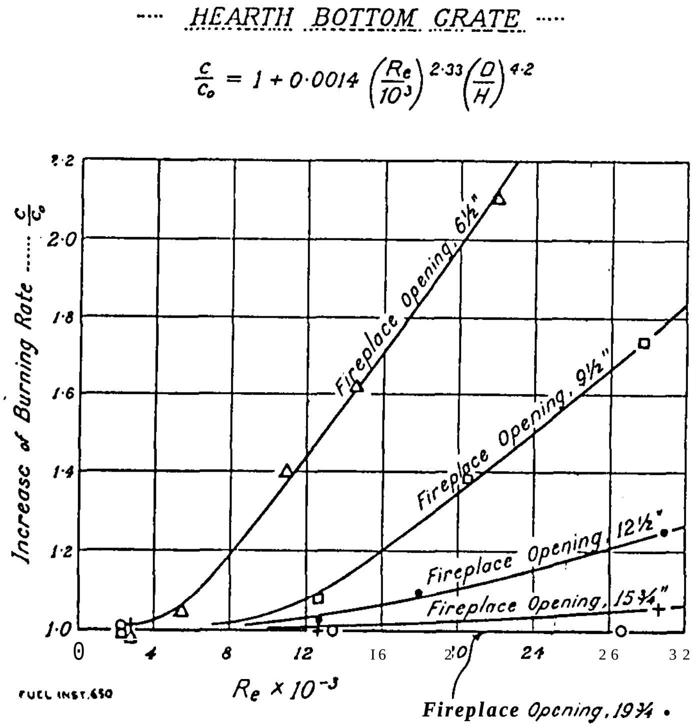


FIG. 45.

to which, by increasing the flow and reducing the fireplace opening, this rate of solution c_0 was found to increase could be expressed as a function Of the Reynolds Number *Re* and the ratio $\frac{H}{D}$ as

$$c = c_0 \left(1 + f\left(Re, \frac{H}{D}\right)\right) \quad . \quad . \quad . \quad (34)$$

The increase of the rate of solution or combustion is, therefore, determined by the equation :

$$\frac{c}{c_0} = 1 + f\left(Re, \frac{H}{D}\right) \quad . \quad . \quad . \quad . \quad (35)$$

in which c_0 and c were furnished by the cspcrimcnts according to equation (33).

(1) *Hearth Bottom-Grate.*—Fig. 4.5 shows the quantitative results of the solution tests obtained with the hearth bottom-grate. The magnitude of reference in this picture is the rate of combustion with which a fire will burn in the open air not connected to any chimney. As the example of the coke brazier shows, any of our fuels, if properly arranged, are able to burn without the help of chimney draught though at low intensity. This natural

rateof burning, which is co-ordinated to zero flow of ventilation air in the room, is markctl as unity in thc cliagram. The ordinate then shows thc amount by which this natural rate of burning can be incrcasccl under thc effect of a chimncy draught. 1.4 mcans, for cxample, that with a chimney the rate of burning is 1.4 times as fast as without a chimncy, or that thc natural rate of burning can be increased by 40 pcr cent. under thc influence of a higher chimney draught. Thc chimney draught as abscissa is expressed as the Rcynolds Numbcr in the throat (scc Fig. 8). 'The different curves refer to various distances between the fire and the tip of the chimney-breast, ordinary fireplaces having an opening of not less than 20 in. The picture shows that the curve for $19\frac{3}{4}$ in. opening entirely coincides with the abscissa which means that at this common distnncc the rate of burning remains entirely unaffected by the chimney pull. It burns with the same constant intensity as if no chimney existed at all. Its rate of burning is not dictatcd, as in other combustion appliances, by the draught, but is exclusively governed by the natural combustion properties of the fuel and the temperature of the bed. The higher the temperature, the faster the combustion. The temperature of the fuel bed, as far as a mean temperature can bc spoken of, depends on the size of the fuel, its arrangement in the grate, especially the thickness of the layer, the reflection of heat back on to the fire by the fireback, the heat emission into the room and thc heat conduction in the fireplace itself. With smaller fuels, the surface-weight ratio increases and more coal is burnt in unit time so long as the packing does not bccome too clcnse. Fuel beds of greater thickness lose less heat by radiation from thc interior and, therefore, keep hotter. Of great importance is as low a conductivity as possible of thc hollow in which the coal rests and the fireplace itself. Heat insulation of the hollow, fireback and sides would improve both thc rate of combustion and radiation.

Fig. 45 shows that it is impossible in the normal hearth bottom-grate to increase the rate of combustion by a higher chimney draught or by opening a damper. This would only result in augmenting the ventilation air, chilling the fireback and cooling the room by carrying back into the chimney the heat that has just been cmittcd. The draught makes its influence felt only if the fireplace opening is reduced below the usual height. It becomes noticeable at about 16 in., but even then the rate of burning at the highest draught is not incrcnscd by more than 5 per cent. A considerable influence would exist with openings as low as 6 in. where the rate of burning could be more than doubled by incrcnsing the chimney draught. But such low fireplace openings arc out of thc question because of their restricted heat emission.

All the curves in Fig. 45 can well be approximated by the equation

$$\frac{c}{c_0} = 1 + 0.0014 \left(\frac{Re}{1000}\right)^{2.33} \left(\frac{D}{H}\right)^{4.2} \quad \ldots (36)$$

in which Re is the Reynolds Number in the throat, D the hydraulic mean depth of the throat and H the height of the fireplace opening.

This empirical expression holds only for the range of velocities tested. It is obvious that a flow velocity must exist at which the maximum velocity of solution or combustion is attained and no further incrcnsc by a higher flow velocity can be accomplished. At this point, which was not reached in the experiments, the curves in Fig. 4.5 must turn to the right and henceforth follow a parallel to the abscissa.

In the raised stool-grate, as opposed to the hearth bottom-grate the floor air streams through the fuel bed as shown in Fig. 23. In Fig. 46 giving the solution results obtained with the stool-grate, the magnitude of reference marked as unity on the ordinate, is again the rate of combustion with which a fuel burns when left alone in the open air without a chimney. The picture shows that in the stool-grate the influence of the draught is much more significant. Already with the normal fireplace opening of 20 in. the rate of combustion is increased through a higher draught by about 60 per cent. With a reduced fireplace opening of about 16 in. it is doubled if the number of air-changes is raised from 2 to 7. This is due to the fact that with a higher draught more air is forced through the grate and the furl, thus blowing the fire.

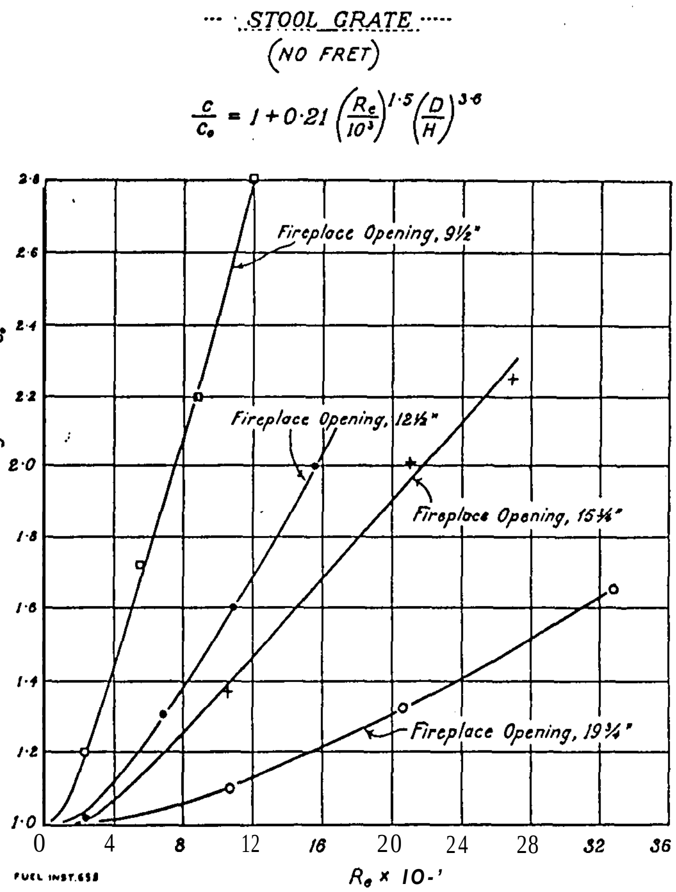


FIG. 46.

The curves for the stool-grate can, for the range covered by the solution tests, be approximated by the cmpiricnl equation

$$\frac{c}{c_0} = 1 + 0.21 \left(\frac{Re}{1000}\right)^{1.5} \left(\frac{D}{H}\right)^{3.6} \quad \ldots (37)$$

The numerical values for the increase of the burning rate shown in Figs. 45 and 46 represent, as already explained, only the influence of the aerodynamic factor as established by the solution experiments. Due to the secondary process of thermal acceleration, the total acceleration caused by increased draught or reduced opening of an actual fireplace can be greater than shown in the diagrams, the purpose of which was to isolate and bring home the effect of the aerodynamic element.

Fig. 47 shows for an air-change of $3\frac{1}{2}$ per hour the difference between a hearth bottom- and a stool-grate. It clearly demonstrates the higher susceptibility towards draught of the stool-grate. The ordinate shows once more the increase of the burning rate, but the abscissa now shows the height of the fireplace opening. This picture, therefore, gives an impression how much the rate of combustion in a given fireplace of 20 in. opening could be increased if the height of the fireplace opening were reduced, such reduction being achievable either by lowering the chimney-breast or by raising the stool-grate. Whilst with the hearth bottom-grate the draught does not exercise any influence on the fire until the opening is reduced to about IO in., at such opening the rate of burning in a stool-grate is already more than doubled.

The diagram also esplains the well-known action of a blower held before the fireplace which forces the air-flow down to the fire and eliminates the dead space, in which it otherwise burns. If, for example, the fireplace opening is reduced by a blower to 5 in., the intensity of burning

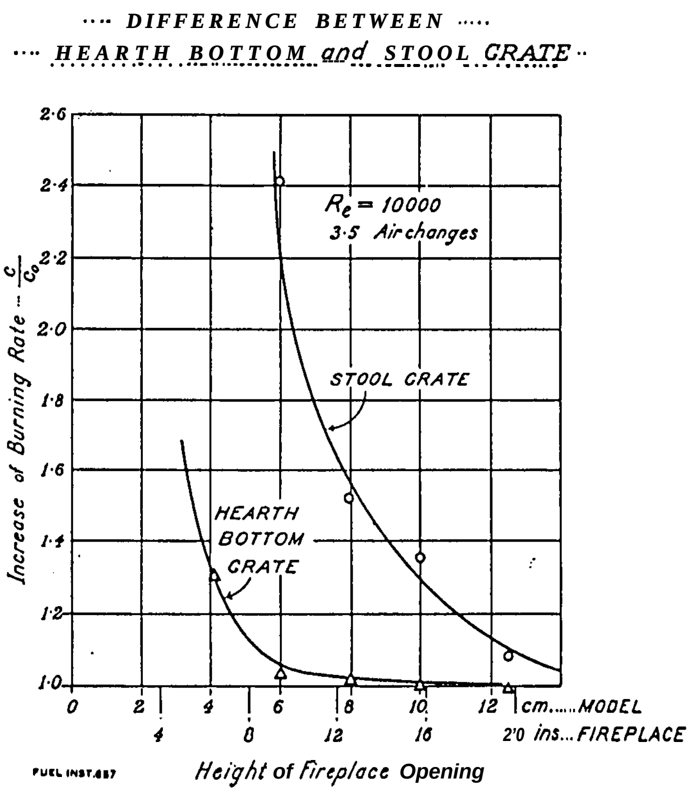


FIG. 47.

is increased by over 50 per cent. A movable blower would, therefore, be the only means of influencing at will, with a given fuel bed, the rate of combustion in a hearth bottom-grate.

In a stool-grate even a minor reduction by some inches of the distance between the coal surface and the chimney-breast can bring about a notable increase of the burning intensity.

These relations between draught and burning rate shown in Figs. 45-47 explain why in the hearth bottom-grate only such fuels can satisfactorily be burnt as possess a high natural combustibility and a suflicient content of volatiles burning above the grate. Such fuels are the younger bituminous coals. Fuels with a lower volatile content or of slower combustibility, like anthracite or coke, need to be burnt on a stool-grate, whereby the action of the draught their sluggish combustion can be intensified. It further follows that the rate of combustion in the stool-grate can and should be controlled by a fret or fender. If such fret tightly shuts the space below the grate and the combustion air is admitted by adjustable openings, a stool-grate in a low fireplace possesses a remarkable degree of flexibility. Dampers in the chimney cannot be considered as effective means of regulating the rate of burning, for the hearth bottom-grate does not react at all to a damper, and its effect on a stool-grate in a fireplace of normal opening and with medium air-changes is only slight. The chief result of a damper consists in a regulation of the quantity of ventilating air. But most dampers of ordinary design create detrimental eddies by which the flow of the combustion gases through the throat and chimney is badly endangered. It would be absurd to eliminate shelf- and canopy eddies by the design of a streamline chimney and then to introduce damper eddies. Avoiding excessive air-flow should, therefore, be achieved by a narrow chimney, with which there is very little need to regulate the rate of ventilation.

On the strength of these tests it can be stated that for the hearth bottom-grate the chimney is not a device for either producing or controlling the flow of the combustion air. For the stool-grate, its influence on the combustion is restricted unless the distance between the grate and the chimney-breast is reduced to about 16 in. Consequently, the main function of a chimney so far as combustion is concerned, is to remove the combustion gases. At the same time it has to fulfil the quite different function of ventilating the room. A relation between combustion and ventilation esists only in so far as the mean temperature of the chimney governs its ventilating performance. These two functions of a chimney, to remove the combustion gases and to induce and take up the ventilation flow, must be combined in such a way that neither disturbs nor impairs the other. These two tasks—and not the production of draught for the fire—should be the decisive factors for the design and arrangement of chimneys.

C. *The Natural Rate of Combustion.*

The motion towards the burning fuel of the combustion air is effected by the buoyancy caused by the different densities of the hot combustion gases and cold air. But as the solution experiments have revealed, a clear discrimination must be made between a fuel burning in the open air and a fuel in a closed appliance connected to a chimney, two different velocities of flow being produced in both cases. In principle, the velocity is a function of the difference between the two densities γ_{air} and γ_{gas} and the chimney height H.

$$v = const. \times \sqrt{2g\,H\,\frac{\gamma_{air} - \gamma_{gas}}{\gamma_{gas}}} \quad . \quad . \quad (38)$$

γ_{gas} must be understood as the mean density of gas throughout the whole chimney height, corresponding to the mean temperature in the chimney, which is a function of the chimney height and the thermal conditions in the chimney. The gases leaving the chimney can certainly not be cooler than the surrounding air. If, due to great heat losses in the chimney by conduction the lower temperature limit is reached before the exit, then the effective chimney height is lower and the velocity will decline.

The same considerations hold for the free burning fuel without a chimney. Here, again, the effective hydrostatic height for the gas motion is determined by the point at which the gases have been cooled down to air temperature. But, owing to the unrestricted radiation from an open fire and the access to the flame of secondary air, the cooling proceeds much quicker than in a chimney. Even if the initial temperature of the Combustion gases in an open fire were the same as that in a closed appliance, which is not the case, the effective height for the buoyancy of the gas column is much smaller and consequently the velocity of the combustion air caused by this buoyancy is reduced to only a fraction. It can become so small that the reaction vclocity falls below the lowest limit, at which combustion can be maintained.

This velocity of the combustion air, causcd by the natural buoyancy of gases from a free burning fuel, has a great significance for the classification of combustion properties of fuel. It represents nothing less than the natural ability of a fuel to burn. All combustion requires a certain minimum velocity of the combustion air, the production of which is, in the case of a free-burning fire, entirely left to the fuel alone, without the artificial assistance of a chimney. With the free-burning fuel the amount and velocity of the air supply arc exclusively a function of the rate of combustion, quite contrary to the case of appliances with chimneys or other artificial means of draught, with which the rate of combustion is a function of the air supply.

Of course, the quantity of burning fuel and its arrangement play a decisive rôle. With one single lump the limiting " chimney height " of the column of combustion gases becomes so small that combustion cannot be maintained. With larger fuel becls the column of the rising hot gases is thicker, the. process of diluting and cooling takes longer, which results in a greater air velocity. If, therefore, the same volume of coal, for example, the same number of equal cubes were equally arranged in the same testing apparatus, and, after being ignited in always the same manner, were left to tlicmselvcs, typical differences of the combustion velocity will bc found which can be measured by the amount or velocity of air pulled through the fuel by its own reaction. If, at the same time, the fuel were arranged on a balance, the decrease of weight could be rccordctl as depending on the measured air-flow and ‥ magnitudes obtained for the clctermination of the criterion $\frac{d}{t.v} = \frac{c}{v}$. Such a method will supply relative values of the reactivity of cliffcrcnt fuels and furnish a classification of the true combustibility.

The critical air-blast test could be regarded as an attempt on similar lines to determine the relative reactivitics of cokes as the minimum quantity of air necessary for maintaining combustion. But the fundamental difference is the fact that in the critical air-blast test the air is artificially supplied, whereas in the new method the fuel itself produces and controls its specific air-flow.

Such an experimental classification of the combustibility of coals will be not only of general interest but also of particular value for the open fire. For it will indicate the relative suitability of fuels by showing their masimum rate of combustion under free-burning conditions, and thus, combined with the aerodynamic results of the model experiments, permit clear rccommcndntions as to the most suitable fireplace design and the additional chimney draught required for maintaining and controlling the rate of combustion necessary for heating a room.

Conclusion.

The definition at the beginning of this paper of the domestic open fire as a combined appliance for heating and ventilation is not quite comprehensive. There is something more in it which cannot be defined by technical .erms.

For centuries the home fire uscd to bc the ccntrc round which family life gathered. To sit and dream before a burning fire, to look into the glowing light, to watch the ever-changing play of flames appeals to something which is deeply rooted inside ourselves.

Maybe it is an atavistic survival from times when a fire was the most precious asset men could possess. Or it may be the subconscious vcrificntion that it is com-

There is no need to define it, nor can it be measured by inches and per cent. efficiency. But there it is, and we should not lose it.

Certainly, there are more modern means of heating and ventilation, but none which more closely respond to our instincts, none more akin to ourselves. No doubt ninny open fireplaces have their clcfccts ; but most of these can be rcclucccl or entirely cured by improved construction and a proper selection of fuel. It was the aim of my research to contribute to this task ; and thus to help in the clcvelopmcnt and protection of this lovable domestic fire.

Appendix I.

Making of Briquettes.

Various salts were considered with regard to their application, and the first briquettes were made up of potassium carbonate, which gives a saturated solution with a density as high as 1.5. This, however, was found to be an estremcly awkward material to handle owing to its hygroscopic properties and, eventually, sodium chloride (puriss, anhydrous) was chosen as in previous experiments.(12)

A die was constructed from a solid iron block, bored to $1\frac{1}{4}$ in. (31.75 mm.). The lower end was coned to a depth of $\frac{1}{2}$ in. (12.7 mm.) to an angle of about 20" to 30°, and a plug turned to fit this hole and lie flush with the end of the die. A $1\frac{1}{4}$-in. (31.75 mm.) mild steel rod was uscd to apply the pressure.

The salt was ground to pass through 72 B.S. sieve, and the die was filled up loosely with the powder to a height which experiments showed would give briquettes of the most suitable length., The amount of salt was thus chosen by volume and a variation of about $\frac{1}{8}$ in. (3.2 mm.) in 2-in. (SO.8 mm.) briquettes was obtainccl.

The steel rod was inserted and the die placed on the table of an oil-operated press. The table was raised slowly until the pressure corresponded to one of 2,500 atmospheres on the surface of the briquette, and the pressure was then suddenly released and restored eight times at intervals of 10 scconcls. Experiments showed that while four times was insufficient, appreciable change in volume occurring, after eight times very littlc more change occurred.

The cone was then tapped out of the bottom of the die, the die placed on a block with a $1\frac{1}{2}$-in. (38. 1 mm.) hole in it and pressure applied very gently to force the briquette out of the die. It was found that if the briquette started with a jerk it almost invariably cracked across. In general, it was necessary to force the steel rod right through before the briquette was loose.

After removing the briquette, it was necessary to clean the inner surface of the die very carefully with alcohol, to rub off any roughnesses with emery-paper and to lubricate it lightly with glycerine. The latter was chosen owing to the fact that as it is soluble in water, a trace of it on the surface of the briquette would not be so serious as a trncc of oil. If this cleaning process were not carried out thoroughly, the nest briquette would stick in the die and crack across. Great care was necessary that the inner surface of the die was not enlarged too much by the emery-paper when it was possible for small particles of salt to become jnmmctl between the steel rod and the die.

It was also found that the upper end of the steel rod was liable to swell under the pressure and would not then enter the die. Hence it was coned slightly so that it was smaller than the other end.

A good briquette had a clean and smooth outer surface, a density of 2.14 to 2.18, a perfectly homogeneous structure, perpendicular to the axis did not usually crack until the saw was $\frac{1}{8}$ in. to $\frac{1}{4}$ in. (3.2 to 6.3 mm.) from a complete cut. The usual method of cutting up the briquettes was to saw them into slices $\frac{3}{16}$ in. (4.8 mm.) long and then saw each of these slices into six or eight equal parts by diametral cuts.

Appendix II.

The Performance of Solution Experiments.

The model is arranged with all the variable dimensions having the required values, those of particular importance being the chimney width, minimum throat opening,

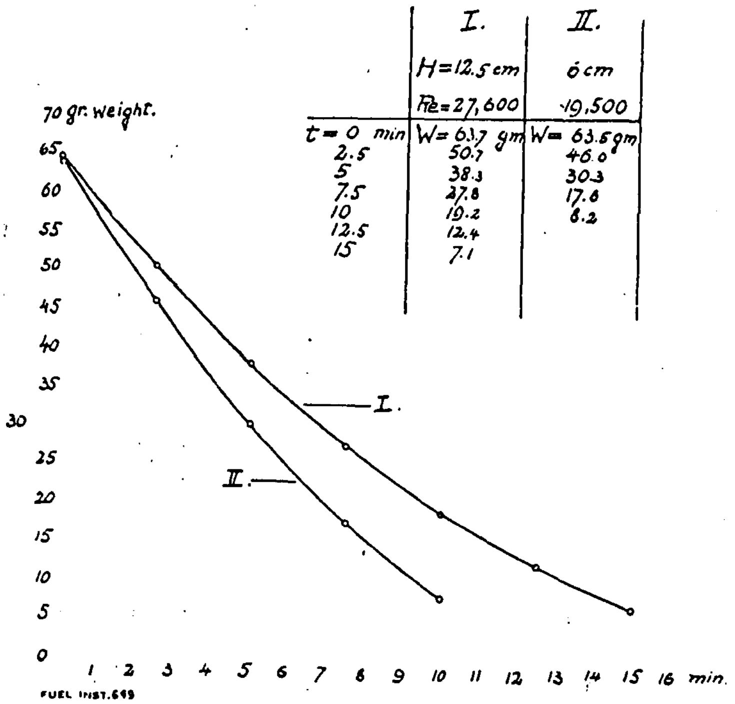


FIG. 13.

height of "floor" above chimney-breast, overlap of fire-back and chimney-breast, and type of grate. It is then filled with water with the outlet valves only slightly open, and the overflow nozzle in the trough is adjusted to give the required height of water. The valves controlling the flow to the large tank and that from the tank to the trough are adjusted so that the tank and the trough have a slight flow through their overflow pipes. Then the required flow through the model is obtained by means of the outlet valve. This flow is measured by means of the difference between one metre water-gauge tubes connected to either side of a standard orifice. Two orifices are used according to whether large or small flows require to be measured.

The grate holder is arranged in such a way that the grate may readily be removed; 50 fragments of briquettes are placed in the grate, which is then suspended by means of copper wire from one arm of a balance of which the pan has been removed. Some stout copper wire on the other arm forms a counterbalance so that the weights in the pan read the actual weight of salt.

When the briquettes have been weighed and arranged in a reasonable standard form in the grate, they are attached to the grate holder, which is placed in the model simultaneously with the starting of a stop-watch.

After the allotted period of time, which varies from 5 to $2\frac{1}{2}$ minutes according to the rate of solution, and is chosen such that about 10 readings are made, the grate holder is rapidly removed, the grate is detached from the holder, alcohol is poured over it from one beaker to another and it is dried by means of a hot blast from an electric hair-drier. Care must be taken that none of the pieces are blown away. The new weight of the briquette is then measured, and after this point has been plotted on the graph, the process is repeated until the weight of salt is less than 20 per cent. of its original weight.

Fig. 13 shows a typical record of an experiment of which 152 were made.

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