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# FORMATION OF A DETONATION WAVE DURING THE BURNING OF GAS IN PIPES

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[Following is a translation of an article by G. D. Salamandra, T. V. Bazhenova, and I. M. Naboko in Zhurnal Tekhnicheskoy Fiziki (Journal of Technical Physics), Vol. XXIX, No. 11, Moscow-Leningrad, November 1959, pages 1354-1359.]

From the moment it was first observed, the phenomenon of detonation has been the subject of numerous investigations. Until recently, the chief technical reason for the interest in the phenomenon of detonation has been the necessity to control it, since transition to detonation combustion usually leads to interruption in the operation of the combustion apparatus or to its destruction.

Despite the great number of both theoretical and experimental works devoted to the study of the detonation propagation of a flame, it is still not entirely clear not only what causes the progressive acceleration of a flame, leading to the transition from slow combustion to detonation, but also how this transition occurs.

Since transition from slow combustion to detonation combustion is connected with a fundamental reorganization of the gas flow and mechanism of reaction transfer, a detailed examination of all stages of predetonation combustion, taking into account the hydrodynamic and chemical factors influencing this process, is of interest. In particular, it is necessary to clarify the role of shock waves appearing before the flame front in the formation of detonation. Depending on its intensity a shock wave, appearing before the flame front, can either cause additional combustion of the gas at the point of its formation, at a distance from the flame front, or create in the region before the flame front a flow of heated, unburned gas in which continuous acceleration of the flame leads to the formation of a detonation wave.

## 1. General picture of the predetonation period

In the present work, the transition from slow combustion to detonation was studied in closed chambers with circular cross section, 42 mm in diameter, and with a square cross section 36.5 x 36.5 mm.

The chambers consisted of four sections of identical cross section. One of the sections was fitted with glass through which the process was recorded. The length of the viewable portion of the chamber was 200 mm. Overall length of the chamber was 2 m. By changing the position of the section containing the glass it was possible to record the process at any point in the chamber. The ends of the chamber were sealed with plugs, in one of which a spark-plug was mounted for igniting the mixture and, in the other, a valve through which the air was drawn off and the chamber fed with the mixture.

Hydrogen-oxygen mixtures were used as fuel since, first of all, combustion of these mixtures proceeds so rapidly that the shock discontinuity and detonation wave are formed at a relatively short distance from the beginning of the combustion chamber and, second, hydrogen-oxygen mixtures belong to the group of low-actinic mixtures, making it easy to obtain good-quality photographs by the schlieren method.

Photography was done by the schlieren method. The process was recorded on film placed on the inner surface of a uniformly revolving drum. The well-known scanning method was employed, as well as a method of high-speed photography by means of special pulse tubes, whose design and operating conditions are described in Reference (1).

Figure 1 shows a photograph of the process of combustion of a stoichiometric mixture of hydrogen and oxygen in the 2-meter chamber with circular cross section, taken by the scanning method. The flame propagates horizontally from left to right, while the film moves in the vertical direction.

Scale markers appear in the photographs in the form of black stripes, traveling parallel to the time axis. Photography was done by the "double-knife" method. Therefore, all optical nonuniformities, regardless of whether they represent regions of rarefaction or compression are recorded as dark areas against a light background.

As seen from the photograph, during the first moments after the mixture is ignited the flame front propagates with acceleration. In front of the flame runs a series of disturbances overtaking one another and cumulating in a shock wave. The velocity of the forming shock wave is about 700 m/sec, and gradually decreases as the wave propagates through the chamber.

After the initial stage of propagation of the flame, characterized by acceleration of the flame, deceleration follows, and then renewed acceleration accompanied by the appearance of additional nonuniformities behind the flame front. Preceding the flame front can be seen clearly the series of disturbances forming a number of shock waves at a relatively short distance from the flame front.

The interaction of the flame with the shock waves arising before the flame front during the predetonation stage of propagation leads to the transition from slow combustion to detonation.

It should be noted that the formation of the shock discontinuity preceding the flame front does not lead, as ordinarily assumed, to the immediate transition from slow combustion to detonation. The detonation wave forms much later and owes its appearance to the interaction between the flame and the shock waves originating before the flame front during the predetonation period of flame propagation.

Following these general remarks describing the process as a whole, let us proceed to a more detailed examination of each of the stages in the process separately.

## 2. The separate stages of the predetonation period

### a) Initial stage of flame propagation

The qualitative explanation of the behavior of the flame during the initial stage of propagation can be reduced to the following: during slow combustion, there occurs in the reaction zone a small drop in pressure together with a significant increase in the specific volume of combustion products in comparison with the specific volume of the explosive mixture before combustion. Owing to the expansion of reaction products, a flow of fresh gas is generated before the flame front. In the first approximation, the problem of the motion of the gas before the flame front during this period can be reduced to the problem of the motion of a gas in front of a piston traveling along a cylinder in accordance with the same law as that by which a flame actually propagates. The series of high-speed photographs (Figure 2) of the combustion process provides evidence that the form of the flame front does not change. Of interest is the slight widening of the boundary of the front, recorded in the photographs; this is connected with an increase in the surface of the flame front owing to the appearance of cells, well defined when the sensitivity of the the schlieren unit was increased (Figure 3).

b) Deceleration stage

As the flame propagates and the space occupied by the burned mixture increases, the expelling action of reaction products diminishes, causing the velocity of flame propagation to decrease.

Finally, the moment is reached when the pressure behind the front becomes lower than the pressure in front. A flow of gas is set up counter to the direction of flame travel. The high-speed photographs taken of the combustion process during this stage support the assumption of an oncoming flow of gas.

The flame front, originally crescent shaped, gradually takes on the characteristic shape of a funnel (Figure 4). The overall surface of the flame front grows larger. The velocity of flame propagation increases.

c) New increase in the velocity of flame propagation

The increase in surface shows up during scanning of the process in the form of a "splitting" of the flame on the light-sensitive film. In this stage, the flame assumes a unique form, assymetric with respect to the axis of the pipe (Figure 5).

The upper part of the front has moved forward in the direction the flame is traveling. The reason for such distortion of the flame can be explained in the following manner: at any given moment, the combustion zone separates out a fresh mixture, of high density, from the lighter combustion products. This heavier mixture tends to spread along the lower part of the chamber, while the combustion products, being lighter, tend to settle in the upper part. Owing to gravity, convection currents are set up which increase the velocity of the flame in the upper portion of the chamber and decrease it in the lower portion.

During this stage of propagation, a large number of disturbances arise before the accelerating flame front, forming shock waves in the vicinity immediately preceding the flame front. The flame propagates through the mixture, which has been "disturbed" by the shock waves.

For determining the state of the gas before the flame front, we have assumed that, in the given stage of propagation, the flame acts as a piston, supporting the gas flow arising behind the shock wave. In that section of the chamber for which calculations were made, this assumption is valid, since in that section no change was observed either in the velocity of the shock wave or of the wave of rarefaction. In this case, the characteristics of the flow behind each shock wave can be calculated from the velocity of the wave, bearing in mind that each new shock wave propagates in the gas disturbed by the preceding wave.

State of the Gas Preceding the Flame Front
During Transition to Detonation

| n (No of wave) | $D_n$, m/sec | $D_n-U_{n-1}$ m/sec | $c_n$, m/sec | $M_n$ | $P_n$, atm | $T_n$, °K | $U_n$, m/sec |
|---|---|---|---|---|---|---|---|
| 0 | - | - | 535 | - | 0.935 | 298 | 0 |
| 1 | 659 | 659 | 572 | 1.23 | 1.5 | 336 | 186 |
| 2 | 829 | 643 | 595 | 1.12 | 1.94 | 362 | 296 |
| 3 | 918 | 621 | 604 | 1.04 | 2.15 | 373 | 340 |
| 4 | 968 | 628 | 612 | 1.04 | 2.36 | 383 | 364 |
| 5 | 1950 | 686 | 635 | 1.12 | 3.07 | 413 | 481 |
| 6 | 1139 | 658 | 643 | 1.03 | 3.33 | 423 | 518 |
| 7 | 1167 | 649 | 644 | 1.01 | 3.41 | 426 | 528 |
| 8 | 1259 | 730 | 672 | 1.13 | 4.53 | 462 | 663 |
| 9 | 1416 | 753 | 697 | 1.12 | 5.89 | 498 | 791 |
| 10 | 1548 | 757 | 717 | 1.08 | 7.11 | 525 | 886 |
| Flame | 1494 | 608 | | | | | |

Note: $D_n$ - velocity of $n^{th}$ shock wave relative to the chamber; $U_n$ - velocity of the gas flow behind the shock wave; $D_n-U_{n-1}$ -- velocity of $n^{th}$ shock wave relative to the motionless gas; $c_n$ - velocity of sound behind the shock wave; $M_n$ - Mach number of shock wave relative to the motionless gas; $P_n$ - pressure behind the shock wave; $T_n$ - gas temperature behind the shock wave.

The results of calculations from one experiment with a stoichiometric mixture of hydrogen and oxygen, a time scan of which is shown in Figure 6, are presented in the table. Results of similar experiments agree closely.

From calculations of the above time scan of the process, it follows that during this stage of development of the process, not only does the flame's velocity of propagation increase, but also its rate of travel relative to the fresh gas. This, apparently, results from the heating of the mixture by the shock waves.

At the moment preceding detonation, a flow of gas arises before the flame front with a temperature approaching that of its ignition point.

Under conditions of high temperature and pressure, the combustion process behind the shock waves progresses so rapidly that there is no possibility of the shock wave and combustion front merging to form a detonation front. This can be seen especially well during the combustion of fuel mixtures in a shock tube pipe, where a combustion front was observed to propagate at detonation velocities in the gas, preheated and compressed by the shock wave, at some distance from this wave (2).

d) Propagation of the flame in the predetonation stage

Figure 7 shows a photograph of the combustion of a stoichiometric mixture of hydrogen and oxygen in the stage immediately preceding the transition from slow combustion to detonation.

During this stage of development of the combustion process, the shock waves formed before the flame front proved to have an especially strong effect on this front.

The shock discontinuity and the flame front form, as it were, a single system, traveling at the same velocity. This system, however, is still not stable: from nucleus to nucleus can be observed a slight change in the form of the flame front.

Behind the flame front, a long comet's tail stretches out in which complete combustion probably takes place; the increase in the velocity of flame propagation with a reduction in the surface of the flame front can be explained by forced combustion, caused by the preliminary preparation of the gas by the shock waves.

## Conclusions

1. The detonation wave in a long pipe is formed as the result of the interaction of the flame front with a series of shock waves forming before the flame front in the predetonation stage.

2. Throughout the predetonation period the form of the flame front undergoes the following changes: a) in the initial stage of propagation immediately following ignition of the mixture, the flame front near the closed end of the chamber has a crescent form, which changes slightly during the entire initial stage of propagation; b) in the deceleration stage, the flame front assumes the characteristic funnel-shaped form, which attests to the presence of an oncoming gas flow counter to the flame front; c) the propagation of the flame in the stage following deceleration is characterized by a significant increase in the surface of the flame, causing an increase in the velocity of flame propagation. Preceding the flame front, a series of shock waves is formed, which gives rise to an accelerating flow of gas before the flame front and increases the temperature of the fresh gas; d) in the stage immediately preceding transition from slow combustion to detonation, the surface of the flame front decreases. Behind the flame front stretches a long comet's tail in which combustion is completed.

In this stage of flame propagation, shock waves arising before the front exert an especially strong influence on the front. The shock wave and flame front constitute a single system traveling with one velocity.

The work was conducted at the Laboratory of the Physics of Combustion, Power Engineering Institute, AS USSR, under the direction of Professor A. S. Predvoditelev.

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Bibliography

1. Salamandra, G. D., I. M. Naboko, and I. K. Sevast'yanova. PTE (in the process of publication).

2. Zaytsev, S. G., and R. I. Soloykhin. DAN SSSR, 22, No 6, 1958

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## FIGURE APPENDIX

Figure 1. Time scan of the combustion of a stoichiometric mixture of hydrogen and oxygen in a chamber with circular cross section.

Figure 2. Initial stage of flame propagation during combustion of a mixture in a chamber with square cross section.

Figure 3. Cellular structure of the flame front.

Figure 4. Flame front in the deceleration stage.

Figure 5. Propagation of the flame in a medium "prepared" by the shock waves.

Figure 6. Time scan of a series of shock waves before the flame front.

Figure 7. Propagation of the flame in the predetonation stage.

-- End --