# Method for determination of the casing-head gas outcome in flares using data of satellite sounding in IR channels by MODIS-type sensors

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A linear, single-parameter model to evaluate casing-head gas outcome in flares using data of satellite sensing in the transmission micro-window from 3.66 to 3.84 μm by sensors like MODIS is presented. In this model the casing-head gas outcome in a flare is proportional to difference between the radiances of the pixel covering the flare and a neighbor background pixels of the sensor. The magnitude of the parameter is determined from the comparison of simultaneous direct measurements of the casing-head gas outcome in the flare and data acquired with MODIS. The proposed model is realized as an original code, calibrated and tested at one of the flares of Khanty-Mansiysk region (61.8N; 77.2E) based on data from MODIS/Terra.

## Introduction

Due to ratification of the Kyoto protocol and its carrying into effect since February 2005, the problem of independent quantitative monitoring of both natural and industrial emissions of greenhouse gases into the atmosphere by each individual region becomes quite urgent. Modern tools and techniques developed for thermal sensing of the Earth from space[1–3] and satellite monitoring of greenhouse gases seems to be promising for being included into the general system of national and international monitoring of the emission of greenhouse gases into the atmosphere. Such satellite sensors as MODIS,[4] GLI,[5] AIRS,[6] etc. created in the frameworks of international programs and launched to polar orbits, show significant capabilities for solving this problem.

We, in Ugra Research Institute of Information Technologies, have made the first attempt to develop a simple single-parameter model and computer codes for determining the casing-head gas outcome in flares from data recorded with MODIS from Terra satellite in real time. The reasons for attracting the MODIS data to solving this problem were the results available in literature on the problem of detecting fires and heat anomalies in the regions of oil and gas flares from MODIS images[7–9] using infrared channels, 3.66–3.84 μm (20th channel), 3.929–3.989 (22nd), 4.02–4.08 (23rd), 4.433–4.498 (24th), and 4.482–4.549 μm (25th channel) within the atmospheric transmission windows. However, no attempts of obtaining quantitative characteristics of casing-head gas outcome in a flare from these data have earlier been made.

The MODIS sensor has spatial resolution in IR channels sufficient for solving such problems, with the pixel size of 1×1 km at nadir observations, which increases at increasing angle of scanning. The data of observations of the oil and gas flares available (under cloudless conditions) show that the flare and its heat plume illuminate 1 to 3 pixels in the aforementioned channels. The spectral brightness of these pixels can be several times greater than the spectral brightness of the background pixels around the flare. Analysis of temperature weighting functions of 20th, 22nd, 23rd, and 25th channels of the MODIS sensor was carried out using the FIRE-ARMS[10]code.

Maxima of the temperature weighting functions characterizing the sensitivity of the signal detected by the sensor in a channel to variations of atmospheric temperature at different heights are localized as follows: 20th channel – on the ground, 22nd and 23rd channels – main maximum at the ground and weak maxima move through the heights of about 1–4 km, 25th channel – maxima move through the heights from about 1 to 7 km and there are no maxima on the ground. This means that the 20th channel well sees radiation of the flare directly from the ground, 22nd and 23rd channels receive radiation of the flare mainly from the ground with small addition of radiation from the lower layers of the atmosphere, and 25th channel receives radiation of the flare mainly from the lower troposphere. Hence, observing the flare and comparing the data of 20th, 23rd, and 25th channels, it is, in principle, possible to observe the configurations of the cross sections of the atmospheric column containing the flare plume in different layers of the troposphere and to estimate its size.

To determine the mean casing-head gas outcome in the flare during the time, which is much longer than the characteristic time of turbulent transfer of the products of burning along and across the flare plume, it seems promising to use simultaneously data of 20th,

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23rd, and 25th channels of the MODIS sensor. If the problem is stated on determination of instant casing-head gas outcome in a flare at the moment of measurement from the satellite, it is sufficient to use only the data of 20th channel. Figure 1 shows an example of the brightness distribution in 20th channel of MODIS for a fragment of the ground, where one of the high-pressure flares of Van-Egan oil deposit is located with the casing-head gas outcome of about $10^5$ m$^3$/hour. The difference in brightness of the pixel covering the flare and the neighbor pixels can be interpreted as the volume of the peak in the plot.

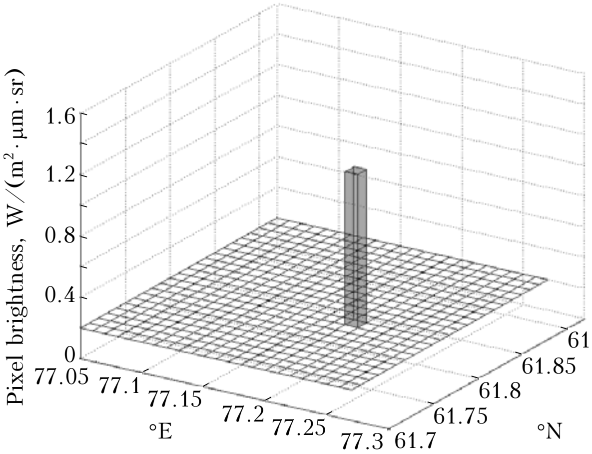


**Fig. 1.** Characteristic example of comparative brightness of the MODIS pixel covering the high-pressure flare and the neighbor pixels at sounding of the area of Van-Egan deposit with the considered sensor from Terra satellite.

The single-parameter model for determination of the instant casing-head gas outcome in a flare from the data of 20th channel of the MODIS sensor, the example of its validation using the results of measurements of hourly mean gas consumption in the flare, and the computer code MODIS_Flares are presented below.

## Model

The proposed method is the model of initial level, which can be further complicated for obtaining more precise results on determination of the casing-head gas outcome in flares from the data of satellite sensing. Further complication of the model can be related with both a more detailed account of the physics of gas burning and with more accurate specification of the optical model of the passive sensing, including the account of meteorological parameters and actual geometry of the flare.

The main simplifying assumptions are as follows:

– the intensity of light emitted by the flare in the wavelength range from 3.66 to 3.85 µm (20th channel of MODIS) along the direction toward the satellite weakly depends on the observation angle;

– the atmosphere is cloudless, cloudy situations were rejected as useless;

– the cloudless atmosphere in the range from 3.66 to 3.84 µm is either quite transparent (low aerosol content) or has constant spectral transmission weakly depending on meteorological conditions;

– heat emission in the flare depends only on the casing-head gas outcome and its specific heat of burning. It is assumed that the fraction of unburnt gas is low;

– only the radiation of the flare is used for determination of the casing-head gas outcome, radiation of the products of burning in the process of their turbulent transfer in the atmosphere is not taken into account.

One can present the spectral density of the radiation flux incident on the MODIS sensor from the ground surface as follows[11]:

$$P_\lambda = R_\lambda \frac{S_{\text{pix}} \cos\theta S_{\text{d}}}{r^2}, \tag{1}$$

where $R_\lambda$ is the spectral density (W/µm) of the energy brightness of radiation coming to the MODIS pixel of the area $S_{\text{pix}}$; $\theta$ is the zenith angle of the satellite, $S_{\text{d}}$ is the area of the detector, $r$ is the distance from the satellite to the center of the MODIS pixel on the ground. It is assumed for simplicity that the zenith angle is constant inside a pixel. In the case a burning flare is inside a MODIS pixel, taking into account the model assumptions, one can write the following formula for the radiation flux incident on the detector:

$$P_\lambda = P_\lambda^0 + CQF_\lambda \frac{S_{\text{d}}}{4\pi r^2}, \tag{2}$$

where $P_\lambda^0$ is the radiation flux from the ground determined by Eq. (1), $Q$ is the casing-head gas outcome, thousands of m$^3$/h, $F_\lambda$ is the distribution density of the spectral energy of the radiation from flare, µm$^{-1}$, that obeys the normalization condition

$$\int\limits_0^\infty F_\lambda \mathrm{d}\lambda = \eta,$$

where $\eta$ is the efficiency of transformation of the energy of burning to the flare radiation. Substituting Eq. (1) into Eq. (2) and reducing the common factors, one can obtain the equality

$$R_\lambda S_{\text{pix}} \cos\theta = R_\lambda^0 S_{\text{pix}} \cos\theta + CQ\frac{F_\lambda}{4\pi}, \tag{3}$$

from which the formula for determination of the casing-head gas outcome follows:

$$Q = \frac{4\pi\left(R_\lambda - R_\lambda^0\right) S_{\text{pix}} \cos\theta}{CF_\lambda}. \tag{4}$$

One can experimentally determine the value $F_\lambda$ by measuring the flare spectra, as well as using the model parameter as adjustment; if necessary, one can determine it separately for each flare. The background value $R_\lambda^0$ was determined from the data on brightness of the MODIS pixels in the vicinity of the flare.

## Calibration of the model

To estimate the possibility of determining the casing-head gas outcome in a flare, MODIS measurements on August 2004 obtained over the flare of high pressure under conditions of the cloudless atmosphere were selected (overall 14 measurements). Measurements over Van-Egan oil deposit were used (61.8°N, 77.2°E). The hourly mean casing-head gas outcome of this flare was known for all selected MODIS data.[12] The calibration dependence of the casing-head gas outcome on the parameter

$$\xi = (R_\lambda - \langle R_\lambda^0 \rangle) S_{\text{pix}},$$

is shown in Fig. 2. Here $R_\lambda$ is the radiation brightness in the 20th channel of MODIS coming from the pixel covering the flare; $\langle R_\lambda^0 \rangle$ is the mean value of the background brightness (in the same channel) of the pixels of neighbor surface.

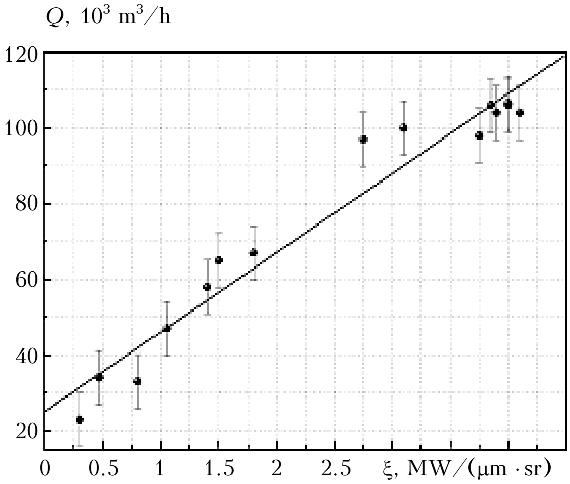


**Fig. 2.** Experimental dependence of the casing-head gas outcome $Q$ in the flare of Van-Egan deposit on $\xi$ (parameter characterizing the brightness of the pixel covering the flare $R_\lambda$ and the background pixels of the 20th channel of MODIS $\langle R_\lambda^0 \rangle$) (dots). The straight line (calibration) is the approximation obtained by the least squares method. The value of the standard deviation $\sigma$ at adjustment of the calibration line is 7.2 $10^3$ m$^3$/h.

The flare was considered at this stage of the development of the model as a plane radiation source fitted into a greater plane source of lower brightness. One can note the uncertainty of the values of the instant casing-head gas outcome in the flare at the moment of sounding by the MODIS sensor as the main source of the error in constructing the plot in Fig. 2, because we had only hourly mean data.

All pixels were used for calculation of $\langle R_\lambda^0 \rangle$, for which the distance $d$ between their centers and the center of the flare pixel meets the inequality $1.1a < d \leq 2a$, where $a$ is the length of the diagonal of the flare pixel. Practically, this means that the pixels next to the pixel nearest to the flare pixel were selected for taking into account the background. All the considered pixels should not be next to the cloud. If the flare has been situated near the cloud edge, it is necessary to ignore the background pixels, which cover the cloud.

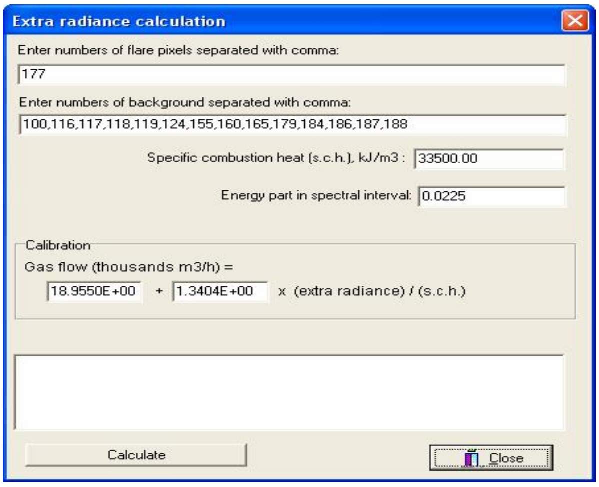
The dependence of the casing-head gas outcome on $\xi$ was approximated using the least squares method by the following linear dependence:

$$Q = p_2 + \frac{p_1}{C}\xi, \tag{5}$$

where $C$ is the specific heat of burning gas, kJ/m$^3$, characteristic of the considered deposit, the quantities $p_1$ and $p_2$ are adjustment parameters. The specific heat of gas burning is included into the calibration dependence, in order to provide the possibility of using the same calibration at the change of the gas composition by changing only this value. It follows from the obtained calibration dependence (see Fig. 2) that this method potentially enables one to determine the casing-head gas outcome in the flare starting from approximately 30 thousands m$^3$/hour.

## MODIS_Flares computer code

The model described above was realized in an original MODIS_Flares computer code under OS Windows for pixel-by-pixel processing of signals from the 20th channel of MODIS and calculating the casing-head gas outcome in the flare. An example of a window of the MODIS_Flares code is shown in Fig. 3.



Enter numbers of flare pixels separated with comma: 177

Enter numbers of background separated with comma: 100,116,117,118,119,124,155,160,165,179,184,186,187,188

Specific combustion heat (s.c.h.), kJ/m3 : 33500.00

Energy part in spectral interval: 0.0225

Calibration

Gas flow (thousands m3/h) = 18.9550E+00 + 1.3404E+00 x (extra radiance) / (s.c.h.)

**Fig. 3.** Window for calculation of the casing-head gas outcome in the flare from the MODIS_Flares computer code.

The casing-head gas outcome in the flare is calculated in the form “Calculation of the excess flow,” which is opened at activation of the “data/calculation” menu box. The pixel numbers, related to the flare and to the background, are determined by the code automatically, however, one can set them manually. To do this, it is necessary to switch on the option "enumerate pixels" in the box "Parameters," and to select the required numbers from the map of pixels shown. After setting the specific heat of gas burning characteristic of the considered deposit, the energy fraction and the calibration parameters, pressing the button "calculate" will cause displaying the following parameters in the text window: the excess flow from the flare, gas outcome calculated by Eq. (4), and the gas consumption calculated using the calibration dependence (5).

The proposed method and the MODIS_Flares code were tested. The values of the casing-head gas outcome in the flare of the Van-Egan deposit in 2005 are shown in Fig. 4. The values were obtained from the MODIS/Terra data using the proposed model and the calibration dependence (see Fig. 2).

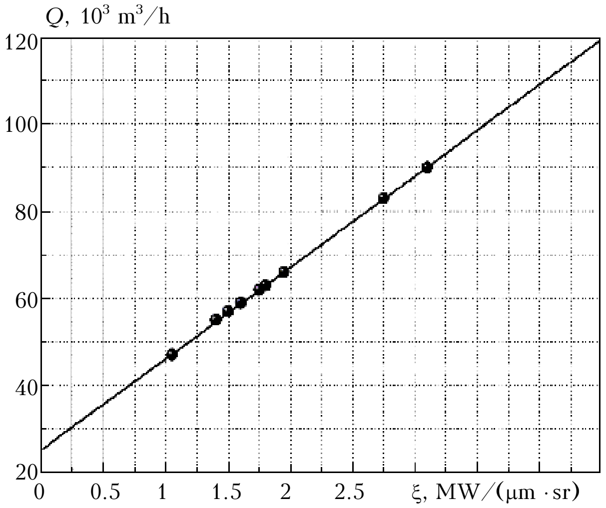


**Fig. 4.** Data of the test monitoring of casing-head gas outcome in the flare of Van Egan deposit in 2005 from the data of sounding with the MODIS/Terra sensor in the 20th channel under cloudless sky conditions.

The error of the method in our case can be characterized by the value of the standard deviation in construction of the presented calibration dependence, the absolute value of which is $\sigma = 7.2 \cdot 10^3$ m$^3$/h.

Let us emphasize that for a better calibration of the model, it is desirable to have much more data than it was available in our case. Small number of points in calibration is caused by the fact that measurements without clouds were rejected, in which the defect pixels were present, i.e., measurements with suspicion of that edge of a cloud could be close, as well as the data where sun glint could be present. Obviously, in order to decrease the effect of different random factors in construction of the calibration dependence, it is necessary to have quite large sample of valid MODIS data. Besides, for a more adequate calibration, it is necessary to use data not on hourly mean gas consumption in the flare, but the results of short-time measurements coordinated in time with acquiring the MODIS data. In order to achieve maximum accuracy of the method, it makes sense to calibrate the model independently for each flare.

## Conclusions

The model and MODIS_Flares computer code (http://remotesensing.ru) presented in this paper can be used as a trial instrument in the MODIS data processing system and quantitative estimation of the flare power and gas consumption in the flares burning the casing-head gas. Satisfactory data on the casing-head gas outcome in the flares obtained from the MODIS data in the frameworks of this simple quantitative model make grounds for being optimistic in future, because there is real possibility of improving it as well as for better calibration of it. Representative and independent set of calibration data on instant gas consumption in the flares also can be obtained in under-flight experiments by means of *in situ* optical measurements of the spectral composition of light fluxes from different flares. The improved and calibrated in such a way model will enable one to improve the accuracy of determination of the casing-head gas outcome in the flares from the data of satellite sensors of the MODIS type and, in principle, can be metrologically certified in future.

It should be noted for conclusion that cloudiness is the negative factor in the methods of spaceborne monitoring of casing-head gas outcome in flares using the sensors operating in infrared range.

For validity of the method, the area around the flare in the MODIS picture (with the size of about 10×10 km) should be cloudless, that is not always realized. However, a single MODIS sensor onboard a satellite on the polar orbit can observe the area of location of the flare every 12 hours, and if data are used from several sensors of the MODIS type, which have the channel from 3.66 to 3.84 μm and operate now on the orbit, the probability of observations in cloudless windows in the region of location of the flares of oil gas burning essentially increases.

In the long-term outlook, if data of microwave (all-weather) sensors are used, the satellite methods for monitoring the casing-head gas outcome in the flares can be weakly dependent on weather conditions and thus become an effective instrument in national and international systems for monitoring of the emissions of greenhouse gases from anthropogenic sources.

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