INTRODUCTION

In our earlier works [1–3], we presented the results of studying the structure and properties (liquidus temperature, density, surface tension) of the slags that form during continuous converting of copper nickel-containing mattes and concentrates in a Vanyukov furnace. It should be noted that the viscosity of slag melts with a significant oxidation potential and a high content of copper and nickel oxides was investigated in a few works (see [4–8]).

The viscosity of a slag melt is one of the properties determining the process of melting: a fluid slag impregnates the refractory lining of a furnace, which decreases its lifetime [9–11]; in a high-viscosity state, a slag decelerates the diffusion and kinetic properties in a bath and leads to the formation of dead zones in furnace cross-flow regions and the foaming of a slag melt, which is typical of bubbling processes [5, 12].

The purpose of this work is to study the viscosities of SiO$_2$–CaO–Al$_2$O$_3$–FeO$_x$–Cu$_2$O–NiO slag melts as a function of the composition and temperature.

EXPERIMENTAL

The slags were prepared from a mixture of chemically pure oxides, which were melted in a high-temperature furnace with a tube graphite heater isolated from the working space by an alundum tube. Oxide samples were introduced into a crucible made of beryllium oxide. The crucible was placed in the furnace heated to a given temperature, and a viscometer spindle was located above it. We used a Shtengel’maier viscometer, which operates in a resonance vibration regime [13, 14]. The relative error of measuring the viscosity by this method is ±5%. The readings of the viscosity of a slag melt were calibrated against the viscosities of standard liquids.

The melt temperature was measured by a PR 30/6 platinum–rhodium thermocouple, one of the thermal junctions of which was situated near the crucible wall at the level of the melt surface.

When the given temperature is reached and a slag is melted, the viscometer spindle was submerged into the slag melt to a depth of 10 mm with a microscrew hoist. The spindle submersion depth was determined using the hoist scale, and the onset of measuring the viscosity was taken to be the time of touching the melt by the spindle, which was detected by an indicator inserted in the measuring diagonal of the Wheatstone bridge. When the spindle was submerged into the slag melt, the resonance of its vibrations was violated. A self-excited oscillator was used to tune the viscometer to resonance. The viscosity of the slag melt was determined from the reading of a digital millivoltmeter connected in parallel to the measuring coil of a ring magnet (millivoltmeter readings are proportional to the vibration amplitude and frequency of the measuring coil).

The composition of a slag melt was varied by the introduction of iron and nickel oxides in an amount at which the (Fe + Ni) content in a slag was changed from 25.5 to 40.2 wt % (table, compositions 1–3). The ratio of fluxing components SiO$_2$/CaO was varied in
the range 0.24–3.9 (compositions 4–6), and the 
(Fe)/(Cu + Ni) ratio in a slag was changed from 1.6 to
0.4 (compositions 7–9).

Thus, the slag viscosity was measured over the wide 
slag composition range characteristic of the oxidizing 
zone of a Vanyukov furnace. The slag of the reducing 
zone is represented by one typical sample (composition 
10).

RESULTS AND DISCUSSION

The literature on the viscosity of slag melts does not 
have a clear definition of the limiting viscosity above 
which a slag cannot be used for a metallurgical process 
under industrial conditions. Nevertheless, as follows 
from indirect estimates, this value fall in the range 30– 
50 P [15]. For the subsequent discussion, the limiting 
viscosity of a slag melt is taken to be 30 P.

Let us begin with the temperature dependence of 
the slag viscosity, which is common for all slags under 
study and affects the mobility of complex anions [4] 
and the solidification of a melt (Fig. 1). An increase in 
the temperature causes the dissociation of complex 
anions or a change in the character of bonds inside 
them (change in the fractions of hetero- and homopoly-
lar bond); as a result, the viscosity of the slag melt 
decreases. A decrease in the temperature leads to 
restructuring and coarsening of complex anions and 
primary and, then, complete solidification, which 
results in an increase in the viscosity of the slag melt.

The curves shown in Fig. 1 have the same type: the 
slag viscosity at high temperatures (>1300°C) does not 
exceed 2 P, and the viscosity decreases sharply as the 
temperature decreases below the primary solidification 
temperature (melt heterogenization). The primary 
solidification temperature agrees well with the 
liquidus temperature.

We now consider the effect of the slag composition 
on the slag viscosity when some composition parameters given in the table are changed. It should be noted 
that earlier [1, 2] we recommended an optimum process 
temperature of 1350°C. Therefore, the slag vis-
cosities in the temperature range 1250–1350°C are 
important under real industrial heat conditions with 
allowance for possible temperature oscillations 
(±100°C).

As is seen from the curves shown in Figs. 2–4, all 
slag melts are fluid and their viscosities do not exceed 
2 P at the recommended process temperature (1350°C) 
irrespective of the slag melt composition. As the tem-
perature decreases, the melt viscosity changes sub-
stantially and the slag composition becomes the deter-
mining parameter.

To a first approximation, the effect of the slag com-
position on the temperature dependence of the slag 
viscosity can be estimated from the interaction of the 
oxide slag components:

(i) A high Fe\textsuperscript{3+} content in a melt favors magnetite 
formation. The introduction of calcium oxide makes it 
possible to transform Fe\textsubscript{2}O\textsubscript{3} into low-melting-point 
calcium ferrites, which decreases \(\eta\).

(ii) Silicon dioxide adds Fe\textsuperscript{2+} to form low-melting-
point Fe\textsubscript{1+x}Si\textsubscript{3-x}O\textsubscript{3} compounds. Calcium oxide pro-
motes the formation of Ca\textsubscript{1+x}Si\textsubscript{3-x} calcium silicate.